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ECONOMIC GEOLOGY OF THE DECOMPOSED COLUMBITE-BEARING GRANITES, JOS PLATEAU, NIGERIA

F. A. WILLIAMS, J. A. MEEHAN, K. L. PAULO, T. U. JOHN, AND H. G. RUSHTON

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ABSTRACT

The Jos-Bukuru Complex comprises intrusive bodies of several different types of alkaline granite and various porphyries. The porphyries are barren of columbite but all the biotite granites contain some columbite as a primary accessory mineral. The range of values is different in each biotite granite and varies within fairly narrow limits. The Rayfield-Gona biotite granite is amongst the richest.

Susceptibility to natural decomposition varies, the Rayfield-Gona Granite being particularly susceptible. Extensive areas of decomposed rock have been preserved by a thin cover of laterite and by mid-Tertiary fluvial and volcanic deposits. The thickness of intensely decomposed Rayfield-Gona Granite commonly exceeds 100 feet. It can be mechanically excavated, disintegrated with a monitor and the columbite recovered by gravity concentration.

For geological mapping rapid empirical methods were devised for identifying different intensely decomposed granites in the field.

Quantitative methods of fragmental petrography, involving the use of desliming cones, superpanners, magnetic separators and acid leaching were developed for (1) confirmation of granite identifications, (2) valuation, (3) analyses to define the major problems of plant scale recovery and mineral dressing.

The habit, percentage and screen analysis of the quartz content is characteristic for some of the granites. Each granite also has a distinctive heavy mineral assemblage. The zircons are particularly distinctive of different granites. They vary in habit, transparency, color and luster with the columbite value. In the Rayfield-Gona Granite radioactivity due to the presence of thorite also varies with the columbite content and the whole heavy mineral assemblage tends to segregate into roughly parallel zones up to hundreds of acres in extent.

The geology of other areas of the Younger Intrusive Series has been less intensively studied using the same methods of descriptive and quantitative fragmental petrography. Columbite-bearing granites, similar to the Rayfield-Gona type are common, and may be preserved in an intensely decomposed condition. The columbite content has not in all places been segregated to payable grade.

It is thought that the descriptive and quantitative methods of fragmental petrography developed for this investigation might prove useful in other parts of the world where intensely decomposed rocks prove difficult to map or are of economic interest for their heavy mineral content.

INTRODUCTION

NIGERIA is the world's leading producer of columbite. There is a small production from pegmatites in the Older Granites and associated eluvial and alluvial deposits. But on the Jos Plateau, until recently, production was entirely from alluvial deposits as a byproduct of tin production.

The solid geology of the Jos-Bukuru Complex was elucidated by MacLeod (6). The investigation of the decomposed granites by the authors of this paper led to the commercial production of primary columbite, which occurs

as an accessory mineral in commercial quantity in one particular type of biotite granite in this complex.

The methods devised for the identification and valuation of intensely decomposed samples of the several members of the Jos-Bukuru Complex were later employed in the geological mapping and preliminary evaluation of other areas of the Younger Intrusive Series, both on and off the Jos Plateau.

PREVIOUS GEOLOGICAL WORK

The Geological Survey of Nigeria was established in 1919 with Dr. J. D. Falconer as Director. In his "The Geology of the Plateau Tinfields," Bulletin No. 1 he gave a comprehensive outline of the geology of the Jos Plateau, then known as the Bauchi Plateau, which provided a sound basis for further investigation. Briefly his description is as follows: An ancient complex of gneisses, schists, and gneissose granites was invaded by a Younger Granite batholith, the higher portions of which were subsequently exposed in the course of denudation. These were subject to a long period of erosion and then were partly covered by alluvial, eluvial and volcanic deposits, which Dr. Falconer called the Fluvio-Volcanic Series. With the elevation of the plateau, probably in Mio-Pliocene times, another cycle of erosion ensued and this Fluvio-Volcanic land surface was much dissected by the rejuvenated streams, leaving high plateaux of old land surface and isolated flat-topped hills. During Recent times, a long period of erosion, accompanied by volcanic activity, occurred and extensive areas of the Plateau were flooded with basaltic lava which not only filled the valleys, covering over the tin-bearing deposits on their floors, but also buried partly eroded Fluvio-Volcanics. Falconer recognized the Younger Biotite Granites as the main source of the alluvial tin and mapped the seven main outcrops of Younger Granite on the Plateau. He described these in some detail and distinguished between biotite and riebeckite granite. He also noted variations in texture in the Younger Biotite Granite, but did not suggest that these granites of different texture belonged to separate intrusions.

In 1946 Amalgamated Tin Mines of Nigeria Ltd. engaged the Aircraft Operating Company of Africa to make an aerial survey of the Plateau. Dr. Mackay et al. (5) made some use of these photographs in their Resurvey of the Plateau Tinfields (1945–1948). In this bulletin they give a useful summary of all the available geological knowledge relating to the Plateau tinfields, and, while accepting the original outline of Dr. Falconer as being substantially correct, they were able to amplify it, and to map the Younger Intrusive Series in more detail. The Younger Intrusive Series was found to occupy an area of 585 square miles, most of which was biotite granite, the remainder being acid porphyries, rhyolites and subordinate riebeckite granites and gabbros. Again no attempt was made to map the separate intrusions within the biotite granite. This was not attempted till 1951, when J. E. Rockingham of the G.S.N., working in conjunction with Amalgamated Tin Mines of Nigeria Ltd., initiated an attempt to distinguish and map the different intrusions of the Younger Biotite Granite of the Jos-Bukuru Complex. W. N. MacLeod,

who followed Rockingham as resident geologist in Jos, was able to complete the work that he had begun. MacLeod separated the Jos-Bukuru biotite granites into several phases that could be identified in the field as separate intrusions. He mapped these different granites, described them, and indicated the relative importance of each as a potential source of columbite. The mapping of MacLeod was based mainly on the evidence of outcrops. Contacts were generalized across areas covered by drift. Considerable areas were mapped as Fluvio-Volcanic Series or as alluvium without elucidating the geology of the underlying rocks. MacLeod's work was a valuable contribution in that it disclosed the pattern on which the Younger Biotite Granites

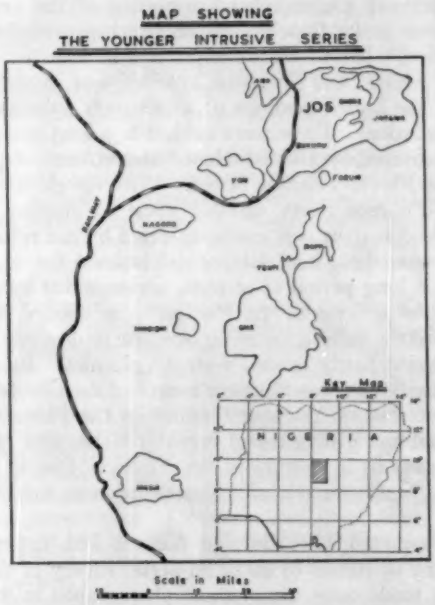

FIG. 1. Map showing the Younger Intrusive series.

had been intruded and thus provided a framework for further investigation. The work done by the geological staff of Amalgamated Tin Mines of Nigeria Limited towards elucidating the geology of decomposed granite in selected areas mostly covered by remnants of the Fluvio-Volcanic Series, recent alluvium and drift, with particular regard to economic aspects, is the project described in this paper.

The history of mineral production on the Plateau goes back to the beginning of this century when agents of the Niger Company proved the existence of tinstone in payable quantities in the Delimi River. This was followed by the Mineral Survey of Northern Nigeria (1904–1909) which found cassiterite

in widely scattered areas in the provinces of Bauchi, Kano, Nassarawa and Zaria, but it was not until after Colonel Laws had ventured into the Plateau area 1903–1910 and pacified the hostile natives, that much capital was attracted to the industry, and the possibilities of the Nigerian tin industry began to be realized. Between 1910 and 1919 when, as mentioned above, the Nigerian Geological Survey was established, expansion was very rapid. In 1909 the Niger Co. was the only tin producer, with a production in that year of 458 long tons. In 1919 there were eighty producers with a total output of 8,174 long tons. The presence of columbite was suspected in Plateau tin alluvials for some time before 1916, when A. S. Williams (9) separated a quantity of a shining black mineral which was causing trouble in tin-dressing, and by means of an ingenious home-made goniometer was able to measure its interfacial angles and definitely identify it as columbite. Since columbite had at that time no market value it continued to be regarded for many years merely as a troublesome impurity of the more valuable tinstone concentrates. Even after 1933, when it was first sold, the price was much lower than that for cassiterite and it was consequently regarded as a more or less unimportant by-product of that more valuable mineral. During the nineteen-forties, however, when the price of columbite gradually rose and it began to be more generally recognized as a saleable product, interest was directed towards this mineral and several writers, e.g., Haag (2) Webb (8) and Tattam (7), wrote papers treating different aspects of the subject. Webb's contribution was perhaps the most noteworthy for in it he outlined simple field methods for identifying and estimating columbite in concentrates, and suggested a nomenclature for specific sub-divisions of the columbite-tantalite series.

Since columbite was found only in association with cassiterite it was assumed, for lack of evidence to the contrary, that columbite was derived from the same lodes and greisens as were thought to be the main, if not the sole source of the tin and tungsten ores. In 1945, however, the late Colonel Dent-Young (3) found columbite in the Younger Biotite Granites of Rukuba and Liruei and in 1950 John and Paulo (4) prepared a slide of Younger Granite from Rukuba in which a crystal of columbite was seen in textural association with the other granite constituents. MacLeod, about this time, working in the Geological Survey laboratory in Kaduna, evolved a fairly rapid technique for the determination by mechanical means of the "free" columbite content of decomposed granite. Briefly this method consisted of disintegrating by hand, under water, a six-pound sample of bedrock, screening off the + 20 (I.M.M.) mesh fraction, concentrating the residue on a superpanner and separating the magnetics with an electromagnet, the columbite content being determined by weighing and grain counting. The term "free" is used to denote that portion of the total columbite content which is freed from the decomposed rock by disintegration by hand under water. It is not equivalent to the full columbite content of the rock for it excludes that which is included in quartz grains or undecomposed feldspar. This value represents the optimum recovery theoretically obtainable by wet-gravity methods at plant scale. Rockingham, about this time, using this method, and working in conjunction with Amalgamated Tin Mines of Nigeria Ltd., sampled decomposed bedrocks over wide areas,

and, having found values up to 0.4 lb per cubic yard, suggested that selected areas, particularly those under Fluvio-Volcanics where the decomposition was likely to be deepest, had a possible future as a source of primary columbite which could be recovered by methods generally restricted to alluvials. MacLeod continued the sampling in conjunction with his fieldwork mentioned above, and having mapped the granites as separate phases, was able to associate the higher columbite values with a particular type of granite, namely his Rayfield-Gona phase. Thus the stage was set for the development of the field and laboratory techniques for proving primary columbite and cassiterite reserves, which are described in this paper.

JOS-BUKURU COMPLEX

In 1952 the Geological Survey of Nigeria issued a map of the Jos-Bukuru Complex, together with a short report in which were described several separate intrusions within the major mass (6). The structural pattern revealed by this map proved to be very useful as a guide for selecting the most promising areas of drift-covered country in which to seek extensions of any particular granite. Later, other granite masses, the Ropp-Tenti and the Sha and Mada Hills Complexes were partly mapped by the geological staff of Amalgamated Tin Mines of Nigeria, Ltd. and the first two of these were afterwards studied and mapped by the Geological Survey of Nigeria.

The Jos-Bukuru Younger Granite Complex covers an area of about 120 square miles. The geology has been described by MacLeod (6). This massif comprises intrusions of several phases of biotite granite and porphyry, which can be distinguished from each other by their texture and mineralogy and are classified as follows:

6. Late Acid and Basic Dikes
5. Late Granites
   Rayfield-Gona Phase (Biotite)
   Bukuru-Sabon Gida Phase (Biotite)
   Delimi Phase (Biotite)
4. Late Granite Porphyry. The Shen-Kuru Complex
3. Early Granites
   (iii) N'gell Phase (Biotite)
   (ii) Shere Phase (Riebeckite)
   (i) Jos Phase (Biotite)
2. Early Granite Porphyry
1. Rhyolite

The work of the geological staff of Amalgamated Tin Mines of Nigeria Ltd. was restricted in the Jos-Bukuru area to the biotite granites and the late granite porphyry, which are described briefly below.

The N'gell Granite is intrusive into the Jos Phase, and the late granite porphyry and late granites are intrusive into the N'gell Phase, but the age relationships of these later granites have not been determined. The Jos Granite has a coarse equigranular texture over practically its whole extent except near

its contacts, where microgranite and complex hybrid rocks are formed. In hand specimen it is characterized by felspar crystals 0.5–1.5 cm in diameter and by large biotite flakes. Ilmenite and monazite abound as accessory minerals. It generally outcrops as high hills with well developed vertical joints, horizontal sheeting, and large rounded tors. The N'gell Granite is invariably finer grained than the Jos Phase with a greater variation in size of felspar, crystals ranging from 0.2–1.0 cm in diameter. The quartz and biotite are also finer grained, the former occurring as chains of crystals and the latter as large isolated plates, or as fine dispersions within the felspar. In outcrop this granite resembles the Jos Phase, but horizontal sheeting is not so well developed and reticulate weathering is more common. This rock also shows porphyritic and microgranitic variations near its contacts.

The Shen-Kuru Granite Porphyry complex shows a great variety of rock types. The most abundant are a hornblende microgranite, which has undergone extensive hybridization with earlier types, and a medium-grained hornblende granite with blue felspar. Most of the Shen-Kuru granite porphyries can be distinguished in the field by their dark bluish color when freshly broken. The Bukuru and Sabon Gida granites are also of several types. They are variable in texture, the commonest type being a fine-grained, inequigranular granite resembling the N'gell Phase, but finer grained and generally richer in biotite. Hybridization and marginal microgranites are common. A feature of these granites particularly useful for field identification is the fractured nature of their quartz, which tends to disintegrate into sharp-angled splinters when in the decomposed state. The Delimi Granite is invariably fine grained and has an equigranular texture giving it a sugary appearance. The quartz crystals are 0.2–0.3 cm in diameter and tend to form in clusters. The Rayfield-Gona and Forum Granites are very similar and are probably local variations of the same rock. They are fine grained equigranular rocks similar in texture to the Delimi Granite. Jointing is close and irregular and weathering usually produces low outcrops of white boulders. They are very readily decomposed and large areas where no outcrops of these rocks occur have been proved by drilling. Microgranites and porphyritic hybrid rocks are commonly found near the contacts.

The Jos-Bukuru massif is situated in an area with a general elevation of about four thousand feet. It is a typical inselberg topography with residual granite hills rising out of plains of Fluvio-Volcanics, alluvium or Recent basalt. Some of the granite types described above have their own very distinctive topography. The Jos and N'gell Granites commonly form high, rugged, blocky outcrops. The Rayfield-Gona Granite forms low flat outcrops or is buried under later deposits, and Shen-Kuru normally forms high hills of very regular outline. A study of the topography can often be a useful guide to the location of contacts between these different intrusions.

Distribution of columbite varies in the different granites. The richest are the Rayfield-Gona phase and the closely related Forum phase, which generally contain more than 0.4 lb of free columbite per ton, and segregations of columbite within these granites may have values of several pounds of columbite per ton. The range of values in the several phases as indicated by our determinations

is recorded in Table 5. These figures represent the values in terms of free columbite as described in an earlier part of this paper.

A common feature of the contacts between these granites is the occurrence of hybrid zones, which in places attain a width of some hundreds of yards. These hybrids add to the difficulty of outcrop mapping, for many of the visible characteristics of both adjacent rocks are evident and the delineation of contacts is often an arbitrary decision. They appear to be, for the most part, merely mechanical mixtures of the original granites with all the characteristics of the quartz and other constituent particles of undecomposed minerals faithfully preserved. Such terms as Rayfield Gona N'gell hybrid, Rayfield-Gona slightly hybridized with Bukuru phase, etc. have to be used to describe the many variations. Thus a Jos/Rayfield-Gona hybrid might be found to contain both the large rounded bluish-grey quartz grains of the Jos Granite and the smaller equidimensional quartz of the Rayfield-Gona phase. It would also be found in the laboratory to have the yellow zircon of the Jos phase and the muddy brown zircon of the Rayfield-Gona phase. Most of the other mineral types commonly found in both granites would be found in various proportions. The columbite content of hybrids is also found to be extremely irregular and is commonly not directly related to the relative proportions in which the quartz distinctive of the parent rocks is mixed.

FIELDWORK

The fieldwork connected with this project was undertaken with the object of locating and proving primary columbite and cassiterite reserves. It was necessary

(I) To elucidate the geology beneath Fluvio-Volcanics and alluvium, and to relate it to outcrop geology.

(II) To locate areas of higher than average columbite and cassiterite values in decomposed bedrock.

(III) To correlate the geology and mining of primary and alluvial deposits of columbite and cassiterite.

Alluvial mining for tin and later for tin and columbite had been carried on on the plateau for the last forty years, and some knowledge of sub-surface topography had been gained by levelling drill holes and working out bedrock contours. Further drilling in connection with bedrock identification and evaluation had provided more information about the old drainage pattern. In order to study and identify the decomposed rocks beneath the drift it was first necessary to have some suitable method of obtaining samples, and having obtained them, to be able to evaluate them in terms of free columbite; and for purposes of mapping, to identify from the decomposed sample, the granite type from which it was derived. Banka drills already in use on this property were used for obtaining samples. As the granites were very decomposed, the making of rock slides would have been slow and difficult. A technique of fragmental petrography was therefore adopted in which a study was made of the undecomposed minerals of decomposed granites. This technique could

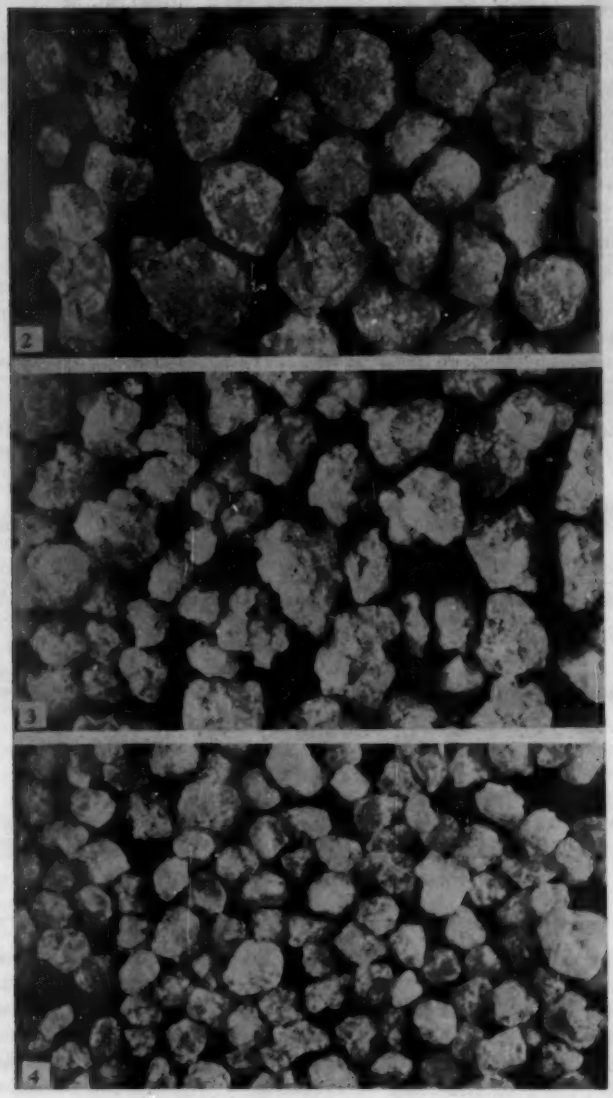

FIG. 2. Quartz from Jos Phase. × 4.
FIG. 3. Quartz from Ngell Phase. × 4.
FIG. 4. Quartz from Rayfield Gona Phase. × 4.

be applied to identification of decomposed rock samples in the field. For field identification, types of quartz were found to be a useful guide towards identification of different granite types (Figs. 2, 3 and 4). Further useful aids were color, characteristic texture, and friability of the sun-dried drill samples.

Some of these characteristics are shown in Table 1.

Friability was tested by crushing a piece of sundried drill core in the hand. Rayfield-Gona and Forum granites readily distegrated into quartz grains and dust, but other decomposed granite samples on drying formed hard resistant cakes. Identification of Bukuru-Sabon Gida granites could often be verified by running a finger nail across quartz grains in the sundried drill core. These would usually break up into sharp-angled splinters.

TABLE 1

Granite type	Quartz characteristics	Texture	Common color
Jos	Large bluish, roughly rounded with secondary overgrowth. Fig. 2	Coarse with large felspars	Dark brown to red
N'gell	Not so coarse as above, colorless, composite, often showing chain structure. Fig. 3	Medium to coarse with irregular felspathic outlines	As above
Rayfield-Gona	Fine to medium, colorless, single and composite grains, roughly equidimensional. Fig. 4	Very even distribution of quartz and felspar	White, gray or pink
Bukuru-Sabon Gida	Medium (some coarse), colorless, composite and singular, breaks into splinters. Many frosted and has tendency to form bi-pyramids	Uneven, medium	Variable
Shen-Kuru	Dull gray, tending to form bi-pyramids. Low percentage	Porphyritic	Generally iron-stained
Forum	Similar to Rayfield-Gona	Similar to Rayfield-Gona with sporadic phenocrysts of quartz and felspar	White, gray, or pink
Delimi	Clear gray small grains, very coarsely aggregated, giving spongy appearance. High percentage	Fine, even grained	White, gray, or pink

Concurrently with the identification of decomposed bedrock, surface maps were prepared, showing the outcrop geology, topography, roads, and alluvial mining development. The sub-surface geology was added to these maps. Systematic drilling and evaluation of columbite and tin values in bedrock are described in another part of this paper. This drilling was supervised by a prospector, the geologist being concerned only with the identification of the drill cores before they were sent for assay, but when a new area was being explored a Banka drill gang was usually put at the disposal of the geologist for preliminary exploratory drilling. The emphasis at this stage was on bedrock identification for purposes of mapping, and preliminary evaluation, the

main object being to select areas of promise for a more intensive drilling campaign and to eliminate worthless areas.

In this mine field, prior to the mining of bedrock, the emphasis was always on tin, columbite in most cases being regarded as a by-product, so that columbite reserves were only roughly calculated and then only in connection with proven tin reserves. With a more complete knowledge of the old drainage pattern and the columbite potential of the rocks drained, it was possible to select areas favorable to rich alluvial columbite concentration. These could then be drilled and evaluated at superpanner standard, and where the alluvial deposit overlay columbite-rich bedrock, the drilling could be continued into the bedrock to the limit of decomposition. It would then be possible to add the combined reserves of alluvial and primary columbite to those of tin and co-ordinate them in one mining program.

LABORATORY METHODS OF IDENTIFICATION

In the laboratory, two main characteristics of the granites are of use in their identification. These are:

(1) The type of quartz and its cumulative percentage screen-analysis.
(2) The heavy mineral assemblage.

Other characteristics of use are the percentage by weight of quartz in the decomposed rock, and the columbite value of the rock.

The method now employed is so designed that each of these characteristics is determined during the process. The method is summarized in the accompanying flow sheet Fig. 5.

The equipment used in the laboratory for this process consists of the following: 1 Pulp balance (domestic scales), 7 Desliming cones, 4 Hotplates 18″ × 12″, 1 Rotap sieve-shaking machine, 2 Sets BS sieves 8″ diameter, 1 Magnetically damped balance 1 div. = 50 mg, 1 Superpanner, 1 Fumes cupboard (cold acid leaching), 2 Drying ovens, 1 Frantz Electromagnetic Separator, 1 Aperiodic balance, sensitivity = 0.1 mg, 2 Binocular microscopes.

The laboratory staff comprises one European mineralogist and three African assistants. The duties are sub-divided with one assistant responsible for the weighing, desliming and drying, one operating the superpanner, and one operating the Frantz separator. The two latter also share the work of screening and weighing the screen-sizes.

With the above equipment and staff, approximately 24 samples of bedrock per week can be dealt with. Normally, a sample takes seven days to complete. The schedule is as follows: 1st day—22 ounces weighed and dried; 2nd day—500 gms. deslimed and dried; 3rd day—Screened, weighed, quartz described and estimated, superpanned, cold acid leach overnight; 4th day—Washed, dried, magnetically separated; 5th day—Magnetics and non-magnetics weighed, examined under microscope, magnetics bulked and hot acid leach commenced; 7th day—Magnetics washed, dried, and checked.

In the laboratory investigation, various new techniques not previously employed by mining companies in Nigeria for sample valuation have had to be introduced. The more important of these are described below.

Elutriation.—The first essential in any treatment of decomposed bedrock samples is to rid them of their content of clay. As the method must also determine accurately the value in terms of free columbite, no significant amount of fine columbite must be lost in this process.

The original desliming equipment consisted of head-pans and was not very satisfactory. Better methods were therefore sought, and the most satisfactory vessel was found to be the type shown in Fig. 6. Here the sample is automatically and continually stirred by the inflow of water, while the decreasing velocity in the upper part of the vessel ensures that any fine columbite caught up in the slime will be freed. As the concentration of slime in the water decreases, the flow can be safely increased.

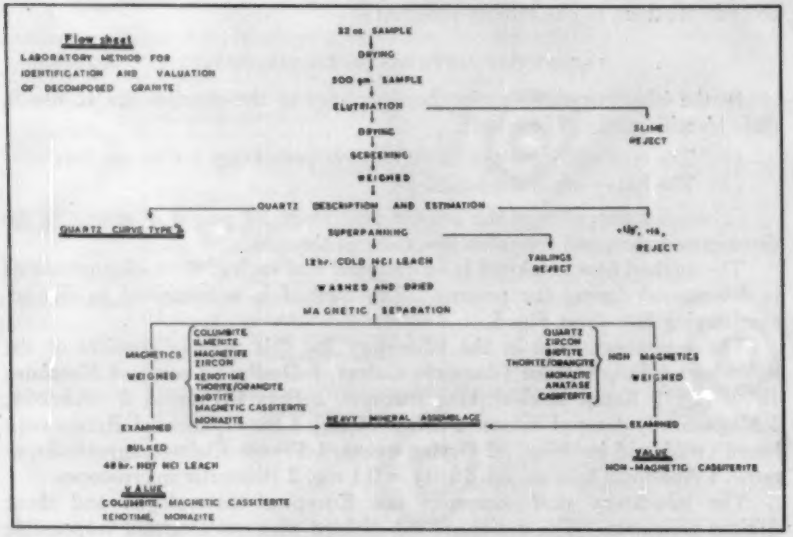

FIG. 5.

Numerous tests by retreating the overflow and superpanning the residue failed to detect any significant loss of fine columbite. The addition of soda ash to the sample to act as a de-flocculent has proved advantageous. It not only increases the speed of desliming, but, by breaking down the clay particles, decreases the risk of any columbite being caught up in them.

Screening.—Each sample is normally passed through the following series of sieves: ⅛", 16 BS, 25 BS, 52 BS, 72 BS, 100 BS, 150 BS.

This selection has been found convenient for routine work, but in cases where additional information is required, more sieves are added.

The Rotap is fitted with a time-switch, and each sample is screened for fifteen minutes.

Superpanning.—To separate the heavy minerals from the deslimed sands,

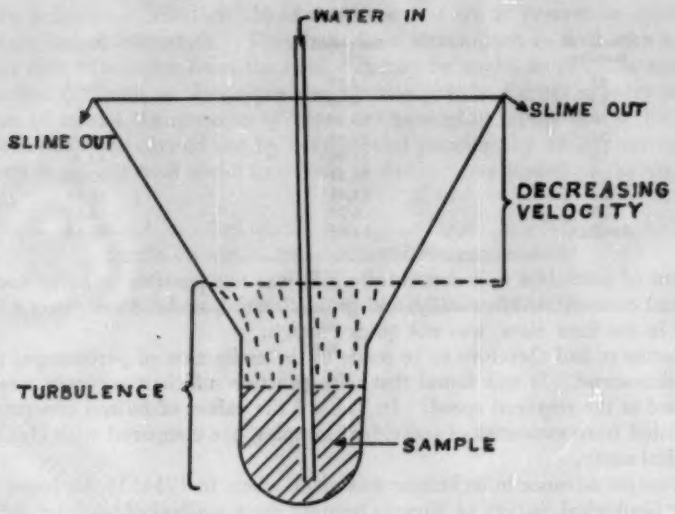

FIG. 6.

a Superpanner made by Infrasizers Ltd., Toronto, is used. The performance of this machine depends to a great extent on the skill of the operator, but with care, and by taking a fairly low-grade concentrate, no losses occur when using screen-sized material. Periodic tests are carried out on the tailings to check that no losses have occurred.

Normally, no heavy minerals are present in the + ⅛" or + 16 BS mesh fractions, and these are discarded once the quartz content estimation and description have been made.

Magnetic Separation.—Several minerals with magnetic permeabilities overlapping that of columbite are present in the concentrates. The settings of the Frantz Separator are adjusted to recover practically all the columbite in a magnetic fraction containing a minimum of minerals of lower magnetic permeability. The settings are as shown in Table 2.

Estimation.—One of the major problems in the evaluation of columbite was the difficulty of obtaining a quick and accurate method of determining the

TABLE 2

Backward Inclination = 15°
Downward Inclination = 25°

Screen fraction	Magnet coil amps
+ 25 BS	0.50
+ 52 BS	0.50
+ 72 BS	0.50
+100 BS	0.55
+150 BS	0.60
−150 BS	0.75

TABLE 3

Number of samples	Estimated %	Assay %
23	7.37	6.11
23	8.10	9.07
30	10.49	16.65
31	29.13	28.92
12	12.99	13.35
20	19.31	22.80
23	13.01	16.71
28	6.77	6.57
Average	14.12	15.10

amount of columbite in a concentrate. It was not possible to assay each individual concentrate chemically, and grain-counting under a microscope, especially in the finer sizes, was not quick enough.

Recourse had therefore to be made to the estimation of percentages under the microscope. It was found that with practice sufficient accuracy could be attained at the required speed. In Table 3 the values of bulked concentrates, calculated from estimates of individual samples, are compared with checks by chemical assay.

A major advance in technique was made when, in 1954, M. P. Jones (10) of the Geological Survey of Nigeria brought out a method of leaching the concentrates for 48 hours in hot concentrated HCl. By this means, all the ilmenite, magnetite, and other iron oxides are completely dissolved. Other magnetic minerals such as zircon and biotite are de-magnetised. The only minerals that are virtually unaffected are xenotime and monazite. These can be removed by the use of cold HF. This affects columbite after a time, and is only used where the final concentrate is particularly impure.

Using this method, the magnetics generally consist of over 90 percent columbite, and as they contain no other black mineral, the margin of error in estimation becomes negligible.

Weight of Cubic Yard.—Columbite-bearing granite is being worked by alluvial methods, for which it is customary to express the value of the ground in pounds per cubic yard. Tests had shown that the dry weight equivalent of a cubic yard of decomposed granite in situ varied appreciably. A conservative figure of 2,400 pounds had been adopted as the standard.

Using this figure, the value of a sample is then given by:

$$\text{Value} = A \times \frac{1}{453.6} \times B \times \frac{453.6}{C} = \frac{AB}{C},$$

where

A = Number of gms of columbite in sample,

B = Weight of one cubic yard (pounds),

C = Weight of sample taken (grammes).

If B = 2,400 lbs and C = 500 gms, then:

$$\text{Value} = A \times \frac{2,400}{500} = A \times 4.80 \text{ lbs/cu yd.}$$

The techniques described above are those that are at present in operation in the geological laboratory. They have been streamlined to deal with a continuous flow of samples from the field. It may be useful to describe some of our earlier methods, as they were also used in part in the preliminary investigation of one of the areas away from our geological laboratory at Bukuru.

Desliming was carried out by very careful panning, by an African assistant, and it usually took about one hour to deslime one pound of decomposed

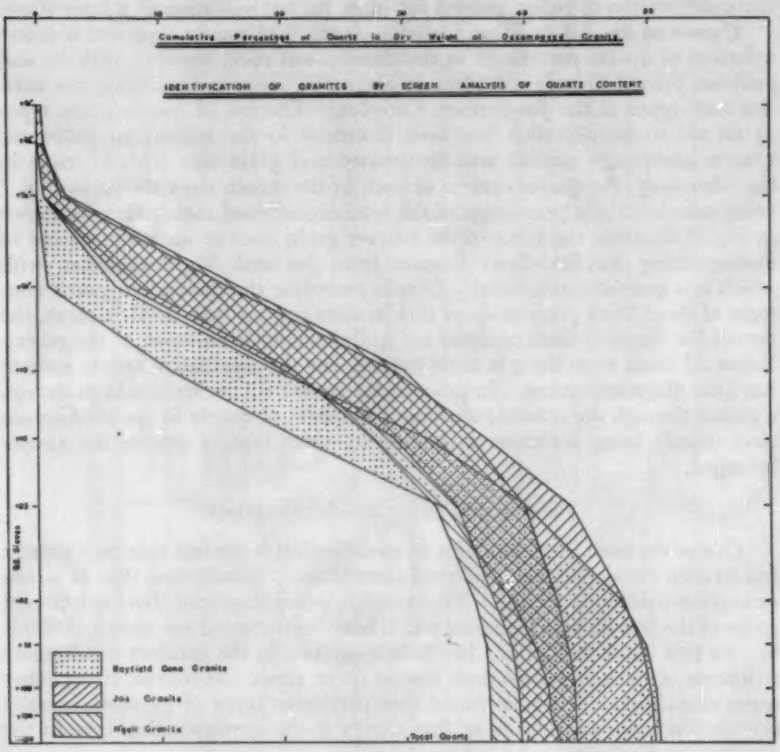
Cumulative Percentages of Quartz in Dry Weight of Decomposed Granite
IDENTIFICATION OF GRANITES BY SCREEN ANALYSIS OF QUARTZ CONTENT
Bukuru Cone Granite
Jos Granite
Wash Granite
Total Quartz

FIG. 7.

bedrock. Drying then took place in the sun, and screening of the dried material was carried out by hand by an assistant. Each screen sized fraction was then small enough to be carefully "panned" in white pie dishes, in which the black columbite and cassiterite could be easily seen. In the finer screen sizes the panning had to be repeated, as it was not possible to prevent some of the fine black minerals from being caught up with the sand; it was sometimes necessary to repeat three or four times in the − 150 BS mesh fraction.

Magnetic separation was effected with an "Eclipse" hand magnet, in which the magnetic strength can be varied. It can be fixed at a setting that attracts all the columbite and minerals of stronger magnetic permeability. The concentrates were weighed with a portable gold balance. Estimation can be carried out with a hand lens, but it is not really satisfactory for the − 150 BS mesh fraction.

Thus with headpans, pie dishes, screens, a hand magnet, small portable balance and a hand lens, a geologist can go into the field and make a preliminary delineation of richer ground for more refined valuation at a later stage.

Quartz as an Aid to Identification.—A study of quartz type and a determination of quartz percentage in the decomposed rock, together with its size analysis, proved to have considerable diagnostic value in identifying the various rock types of the Jos-Bukuru Complex. The use of quartz grain types as an aid to identification has been discussed in the section on fieldwork. Quartz percentage content was determined and grain size analysis made in the laboratory, the quartz content of each of the screen sizes shown in Fig. 7 being calculated as a percentage of the total decomposed rock. Graphs shown in Fig. 7 illustrate the value of the coarser grain sizes of quartz as an aid to distinguishing Rayfield-Gona Granite from Jos and N'gell Granites, with which it is generally associated. Graphs recording the cumulative quartz contents of these three granites show that in sizes coarser than 25 B.S. mesh, the curves for Rayfield-Gona samples are quite distinct from those of the others. Below 25 mesh sizes there is some overlap and the cumulative quartz content has little diagnostic value. In practice the quartz curves were seldom drawn, a glance through the columns showing the weight of quartz in specified screen sizes usually being sufficient to indicate to which type of granite the sample belonged.

JOS-BUKURU COMPLEX—MINERALOGY

One of the most important aids to identification is the fact that each granite has its own distinctive heavy mineral assemblage. Usually one type of zircon or another mineral is typical. The complete assemblages for those component rocks of the Jos-Bukuru Complex which have been studied are shown in Table 4. As this is the area which has been examined in the greatest detail, more is known of its mineralogy than that of other areas. However, in all other areas examined, it has been found that particular types of granite generally contain the same assemblage as that shown in the corresponding type in the Jos-Bukuru Complex.

The names applied to the various types of zircon are purely descriptive, and are used for convenience in the routine examination of samples. The main characteristics of each assemblage are described below.

Jos Granite.—"Straw" zircon is typical of the Jos Granite. It is a straw yellow in color, and the mineral is generally shattered internally, giving a sparkling effect under the microscope. The zircon is elongated parallel to the C-axis, and displays a prism *110*, combined with the pyramid *111*. Although typical, the zircon may however be scarce in the assemblage.

Monazite is commonly present in considerable quantity in the Jos Granite.

TABLE 4

HEAVY MINERAL ASSEMBLAGES OF THE GRANITES OF THE JOS-BUKURU COMPLEX

Mineral	Jos	N'gell	Rayfield-Gona	Bukuru	Shen-Kuru	Forum	Delimi
Zircons "Mud"	Absent	Absent	Common to abundant (typical)	Absent	Absent	Absent	Absent
"Fresh Mud"	Absent	Absent	Absent	Absent	Absent	Common to abundant (typical)	Absent
"Straw"	Scarce to common (typical)	Absent	Absent	Absent	Absent	Absent	Absent
Pale brown translucent to subtranslucent	Rare to scarce	Scarce to common (typical)	Absent to rare	Scarce	Absent	Absent to rare	Rare
Pale brown subtranslucent to murky	Absent	Absent	Absent to rare	Scarce to common (typical)	Absent	Absent to rare	Scarce (mainly in fine sizes)
"Wine and amber"	Absent	Absent to rare	Absent	Rare to scarce (typical)	Absent to rare	Absent	Absent
Colorless, milky and/or clear yellow	Rare to scarce (mainly in fine sizes)	Scarce (only in fine sizes)	Rare to scarce (only in fine sizes)	Rare to scarce (mainly in fine sizes)	Rare to scarce (coarse and elongated) (typical)	Rare to scarce (only in fine sizes)	Rare (only in fine sizes)
Earthy gray, subtranslucent to murky	Absent	Absent	Absent	Absent	Absent	Absent	Scarce (typical ?)

TABLE 4—*Continued*

Mineral	Joa	N'gell	Rayfield-Gona	Bukuru	Shen-Kuru	Forum	Delimi
Monazite	Rare to common (subtranslucent, dull yellow) (typical)	Rare to scarce (yellow)	Rare to scarce (pale yellow)	Rare (yellow)	Absent to scarce (yellow)	Rare to scarce (yellow)	Rare (yellow)
Ilmenite	Rare to common	Rare to scarce	Absent to scarce	Rare to scarce	Scarce to common	Rare to scarce	Rare to scarce
Magnetite	Absent to scarce	Absent to scarce	Absent to rare	Absent to rare	Rare to abundant	Absent to scarce	Rare
Columbite	Absent to rare (prisms and needles, mostly fine)	Rare to scarce (prisms, usually somewhat flattened, relatively coarse)	Scarce to common (prisms, needles, plates some corroded, or in coke-like grains)	Scarce (needles and flattened plates, very well crystallized, high luster)	Absent	Scarce to common (prisms, plates, occasionally corroded, or in irregular grains)	Rare to scarce (prisms and needles)
Thorite/orangite	Absent	Absent	Absent to scarce	Absent	Absent	Absent to rare	Absent
Xenotime	Absent	Absent	Absent to scarce	Absent	Absent	Absent to rare	Absent
Anatase	Absent to scarce	Absent to rare	Absent	Rare to scarce	Absent	Absent	Rare
Amphibole (Hornblende ?)	Absent	Absent	Absent	Absent	Rare to common	Absent	Absent

Scale of Relative Abundance (after Milner)

	Watt's number		Watt's number
Flood	9	Scarce	4
Very abundant	8	Very scarce	3
Abundant	7	Rare	2
Very common	6	Very rare	1
Common	5	Absent	–

It differs from the monazite in the other granites by being almost opaque to subtranslucent and of a dull yellow color.

N'gell Granite.—No mineral can be said to be truly typical of the N'gell Granite, although in all cases the predominant zircon is a pale brown translucent to subtranslucent type. The zircon is normally rather fine, and displays the prism *110*, combined with the pyramid *111*. It is generally somewhat elongated parallel to the C-axis.

Generally, it may be said that the N'gell Granite is characterized more by the lack of zircons typical of the other granites, rather than by any distinctive mineral of its own.

Shen-Kuru Complex.—The zircon typical of the Shen-Kuru Complex is a clear, colorless or yellow type. A few crystals may be milky-white in color also. The zircons are prismatic and the crystals are coarse and markedly elongated parallel to the C-axis. They also display a high lustre. The zircons of this color listed in the assemblages of the other granites do not have this lustre, nor are they nearly so coarse or elongated.

All samples from the Shen-Kuru Complex have a variable content of amphibole, probably hornblende. This is somewhat difficult to identify when in grains from a decomposed rock, but a close inspection will generally reveal the typical amphibole cleavage and/or schiller structure. The amphibole reports in the magnetic fractions along with much magnetite and/or ilmenite.

Delimi Granite.—Although the pale brown, murky type of zircon is a major constituent of the heavy mineral assemblage of the Delimi Granite, the only typical mineral is an earthy-gray colored, sub-translucent to murky zircon. The crystals are prismatic, but display no tendency to be elongated. There appears to be less zircon in the Delimi Granite than in any other of the Second Cycle Granites.

Rayfield-Gona Granite.—"Mud" zircon is typical of the Rayfield-Gona Granite. It is pale to deep-brown in color, and is generally opaque, although some may be subtranslucent. The surface of the crystals is generally somewhat dull. The distinctive feature of this zircon is not so much its color as its habit, which is most commonly the pyramid combined with an extremely short prism. The crystals are therefore invariably short and equidimensional. They are commonly broken. Even if the color and transparency are as described above, no zircon can be described as "mud" zircon unless its habit conforms to the above criteria. There are normally some zircon crystals with inclusions of columbite. The zircon is common in the assemblage, and is generally present even in the coarser sizes, some normally being present in the + 25 BS mesh fraction.

In the richer columbite-bearing areas of Rayfield-Gona Granite, thorite-orangite and xenotime appear, and in these areas they are typical of this granite. In other areas of Rayfield-Gona Granite, they may be absent.

The thorite-orangite occurs as either dark reddish-brown opaque crystals (thorite), or as orange to yellow translucent to opaque crystals (orangite). Both varieties occur as flat tetragonal plates showing a marked development of the basal plane *001* combined with the pyramid *111*. The thorite may also display a short prism.

The xenotime occurs as milky white, pale yellow or buff-colored tetragonal crystals, showing the prism and the basal plane only. The crystals are normally opaque, but a few may be subtranslucent. Generally, two good prismatic cleavages are displayed.

Generally, the monazite in the Rayfield-Gona Granite is of a paler color and is more translucent than that in the other granites.

Bukuru Granite.—The mineral most typical of the Bukuru Granite is a pale brown subtranslucent to murky zircon, with a prismatic habit, commonly displaying a pyramid *111*. This granite is generally difficult to distinguish from the N'gell Granite, but the occurrence of the almost opaque, murky brown zircon, and the absence of the translucent variety, generally serve to distinguish them. Also the zircon in the N'gell Granite is more elongated than that in the Bukuru Granite.

"Wine and amber" zircon is also more or less typical of the Bukuru Granite. It occurs only in the finest sizes, and is never more than scarce in the assemblage. The mineral is translucent and of a wine yellow or amber color. Its habit is prismatic, although the exact forms displayed are difficult to determine owing to the extreme fineness of the crystals.

Anatase is normally present, although not absolutely typical. It is generally black and opaque, but may be green or yellow and subtranslucent. In most cases, the mineral occurs in irregular scales, but a few crystals showing the typical octahedral habit are generally present. The mineral may also show crystals with the octahedron modified with the basal plane.

Forum Granite.—"Fresh mud" zircon is typical of the Forum Granite. It is of a very pale fleshy or a deep brown resinous color. Its habit is the same as that of the "mud" zircon of the Rayfield-Gona Granite. The zircon is more subtranslucent and the lustre is much higher (hence the name given to it) than the zircon of the Rayfield-Gona Granite. Other differences are that the zircon of the Forum Granite has fewer columbite inclusions, a somewhat different color, and the crystals are much more broken.

Columbite.—The columbite from the Younger Granites is generally well-crystallized. The crystals are normally tabular or somewhat elongated parallel to the c-axis. Great variations occur, and extremely flattened plates or very elongated acicular crystals are not uncommon. Pyramid, and to a lesser extent, dome and basal faces are also generally present.

The columbite is invariably black and is opaque even in the thinnest fragments. It is not uncommon for some of the grains to show a blue or, more rarely, a green or yellow irridescence.

The specific gravity is 5.5 ± 0.05. The mineral is slightly softer than quartz. The streak varies from a dark reddish-brown to a light cinnamon-brown. The magnetic permeability of columbite lies between that of ilmenite and monazite, there being some overlap in both directions.

From three determinations on columbite from the richer areas of Rayfield-Gona Granite, the content of combined pentoxides, $(Nb, Ta)_2O_5$, is 76%. The ratio Nb:Ta varies slightly, but the average appears to be about 7:1.

The detailed studies of the Jos-Bukuru Complex show that the type of

crystallization of the columbite is to a certain extent typical of the granite from which it is derived. In this respect, the following generalities apply:

(1) The columbite in the Jos Granite is more elongated than that in the N'gell Granite, which tends to be platy.

(2) The columbite in the Bukuru Granite is distinctive in that the crystals are perfectly-formed needles or plates with a very high lustre. The faces are invariably much brighter than in the columbite from any other of the granites.

(3) In the richest columbite-bearing areas of the Rayfield-Gona Granite, most of the columbite crystals are corroded and pitted, or the mineral occurs in totally anhedral grains with an appearance resembling coke. This also occurs to a lesser extent in some areas of the Forum Granite. This phenomenon has been seen only in areas richer than normal in columbite.

Values.—From the outset of the investigation, it was known (6) that some members of the Jos-Bukuru Complex carried more columbite than others. From the numerous valuations carried out since then, it appears that the value is a characteristic of the rock, and lies within fairly narrow limits (see Table 5).

TABLE 5

Granite	Range of values (lbs/cu yd)	Approx. average value (lbs/cu yd)
Jos	Nil–0.05	0.02
Delimi	0.05–0.15?	0.10?
N'gell	Trace–0.25	0.18
Bukuru	0.10–0.40	0.30
Forum	0.30–6.0	0.50?
Rayfield-Gona	0.40–7.57	0.50

Relation between Type of Zircon and Value of Columbite.—From Table 6 it will be seen that a striking relationship exists between the type of zircon and the columbite content of the rock.

Although not included in the above, it is probable that the Forum and Delimi Granites fit into place in the above table. Too little work has been done on these granites for a definite opinion to be given

It will be seen that as the zircon becomes less elongated, darker in color, more opaque and of a duller luster, so the columbite content of the rock increases.

Cassiterite.—Cassiterite in Nigeria can be divided into two categories on the basis of its origin viz.:

1. Secondary (Hydrothermal)
2. Primary (Accessory).

Mackay, Greenwood and Rockingham (5) consider the secondary cassiterite to be associated with the Younger Granites in veins, stockworks, and greisenized zones within them, the distribution of which they regarded as being random throughout the intrusion. This secondary cassiterite was believed to be the major source of the alluvial tin deposits.

Our investigation of the Jos-Bukuru Complex shows that cassiterite is also present as an accessory mineral in the granites. The distribution of this

TABLE 6

Rock	Average columbite value	Typical zircon			
		Habit	Transparency	Color	Luster
Shen-Kuru Granite Porphyry	Nil	Very elongated	Clear	Clear-yellow	Very high
Jos Granite	0.02	Elongated	Translucent	Straw-yellow	High
N'gell Granite	0.18	Somewhat elongated	Translucent to sub-translucent	Pale-brown	Fairly high
Bukuru Granite	0.30	Somewhat short	Sub-translucent to murky	Pale-brown to brown	Somewhat low
Rayfield-Gona Granite	0.50	Equidimensional	Opaque	Brown to deep brown	Dull

primary cassiterite forms no clear picture, but the following generalizations may be made:

1. Primary cassiterite is not confined to any one granite and the value within any granite may vary from nothing to over one pound per cubic yard.
2. In areas where the granite is richer than normal in columbite, as in the Rayfield-Gona Granite near Rayfield, the content of primary cassiterite is also higher.

Order of Crystallization of the Accessory Minerals.—From the studies of the heavy mineral assemblages it is possible to give the order in which the main minerals crystallized. For all the granites, the following order holds:

1. Cassiterite (accessory)
2. Columbite
3. Zircon.

In the Rayfield-Gona Granite, where more accessory minerals occur, the picture is not so clear, but the following order of crystallization is probable:

Mineral	Recorded as inclusions in:
1. Cassiterite	Columbite, zircon, xenotime, thorite/orangite
2. Columbite	Zircon, xenotime, thorite/orangite
3. Thorite/orangite	Zircon
4. Zircon	Xenotime
5. Xenotime	Not included in any of above

In the above, the role of monazite is not clear, as it has not been recorded as being included in or as including any of the other minerals. In extremely rare cases, exceptions to the above order have been found.

There is a tendency for the minerals to develop in certain mutual orientations to each other. Crystals of columbite including cassiterite tend to have their c-axis at right angles to that of the cassiterite. When a crystal of zircon is found including columbite, the c-axis of the two minerals tend to be parallel.

Discussion.—From the above, it will be seen that it would be possible to distinguish the various members of the Jos-Bukuru Complex in the decom-

posed state by means of their heavy mineral assemblages alone. Not only has the method now used made possible the study of decomposed granites by techniques originally developed in sedimentary studies, but these techniques have been put on a more quantitative basis. The method depends essentially on the recovery of practically all the heavy minerals present, even in the subsieve sizes. The elutriation technique and the superpanner form the basis of the method.

In the case of decomposed rocks, the method is more delicate than the use of thin sections. In thin section petrology, the preferable condition is a perfectly fresh specimen. In our method, the reverse condition holds. No assemblage could be represented completely in the compass of a rock slide, and the minor variations in the character of the zircon would not show in thin section. Also, the manufacture of a section from such decomposed material would be extremely difficult.

In our opinion, it is possible that the techniques described may have a wider application in other parts of the world where intensely decomposed rocks have to be dealt with. It is also possible that much valuable information could be gained in the case of hard rocks which, after preliminary crushing, would be amenable to treatment.

VALUATION OF RESERVES

Preliminary drilling in depth soon indicated that the maximum thickness of decomposed granite in any area might exceed 100 feet. The range of total depths to be expected in a particular area to be drilled could be roughly anticipated from the depths of overburden, if any, recorded by previous drilling of alluvial tin leads and estimates of the thickness of decomposed granite which had probably been eroded. In order to speed up the developement program and to make use of available equipment to the best advantage, hand operated Banka drills were used in shallow ground and percussion drills in deep ground. As far as possible, hand drilling was confined to ground that was expected to be less than 100 feet deep, and preferably shallower.

A proportion of the hand drilled holes failed to reach hard rock, sometimes due to the depth of the ground but more frequently due to the existence of a zone of very soft, waterlogged, decomposed granite from which a sample could not be recovered with a screw auger. Nevertheless, hand drilling served for the rapid scout valuation of some extensive tracts of country and for the valuation of some high-grade reserves to sufficient depths for planning mining operations.

The uniformity of distribution of the columbite in the decomposed granite warranted using a fairly wide bore spacing. Square grids were adopted. The relatively cheap hand drilling was usually spaced at 200-foot intervals and the more expensive power drilling at 400-foot intervals. Some areas of marginal value may be drilled at closer intervals later.

Hand-drilled holes were put down with a screw auger and usually without casing. Only core from the tip of the tapered auger was accepted. This spot sampling was conveniently quick and was justified by the uniformity of distribution of values. Power-drilled holes were put down with an earth-socket

driven in by the jars. Casing was used in soft ground and to seal off alluvial wash. Penetration was always to hard rock. Solid cores were obtained. These were split in two longitudinally and channel sampled. Samples from both hand and power drill holes were bagged in ten-foot sections.

The sectional values of the power drilled holes revealed, as would be expected, an appreciable diminution in the yield of "free" columbite from the semi-decomposed granite encountered before reaching hard rock. Subject to closer boring it should thus be possible to define an economic mining depth in areas of marginal value.

Surplus core was laid out in the field in ten foot sections for inspection by the geologists. Being familiar with the decomposed granites of any particular area, from the preceding geological investigations, the geologists could usually identify sectional cores in the field. In doubtful cases a sample would be taken to the laboratory for partial or complete analysis by the methods previously described. The identifications of the granite types and hybrids penetrated were recorded in color on bore plans. A representative number of samples were also taken from each area for screen analysis of the columbite content for use later in estimating recoverable values.

The valuation of sectional bore samples was carried out in two separate buildings; one for desliming, concentration and magnetic separation, the other for digestion of concentrates with hydrochloric acid. The former was equipped with a pulp balance, 2 hot plates, 45 desliming cones, 7 superpanners and 4 electro-magnets. The other building contained a total of 18 hot plates, each 24″ × 18″, housed in 3 fumes cupboards. The average throughput of bore samples was 250 per week. The fumes cupboards were used for samples from other sources as well.

In order to achieve this rate of throughput the methods devised for the combined identification and valuation of samples for geological mapping, as previously described, were modified. Geological information and screen analyses of the mineral contents were not required from these samples. A slightly lower standard of accuracy for the valuation of individual samples was accepted, but the overall accuracy was maintained by chemical assays of bulked concentrates representing a number of bores.

Groups of contiguous bores were selected on the basis of the identifications of the cores in the field as recorded on the maps. Similar granites and hybrids usually yielded concentrates of roughly similar composition within a limited range of values.

Samples received weighed 15–20 lbs from which a representative 3 lbs was taken for valuation, the moisture content being determined on a separate fraction. The sample was disintegrated by hand under water, the plus 8 B.S. mesh size screened off, the undersize carefully deslimed in the cones, and the residue superpanned without sizing. The concentrates were then zinc blocked, dried and magnetically separated to extract practically all the columbite as a low-grade concentrate. This was leached for 48 hours in hot concentrated hydrochloric acid to decompose iron oxides and ilmenite and to demagnetise magnetic zircon. The leached concentrates were then again zinc blocked, dried and magnetically separated to yield a columbite concentrate with only

a small amount of impurity, mainly magnetic cassiterite, xenotime, and monazite. After weighing, the columbite and magnetic cassiterite of this fraction and the cassiterite content of the combined two non-magnetic fractions were estimated under a binocular microscope.

To account for the small losses of fine mineral which occurred in superpanning *unsized* sands the bulked tailing from the whole group was dried, screened through a 100 B.S. mesh and the undersize retreated. As a little fine columbite tended to remain in the non-magnetic fractions these were also bulked and retreated. Finally the bulked magnetic and non-magnetic concentrates, to which recoveries from retreatment had been added, were chemically assayed to determine their columbite and cassiterite content. A correction was then applied to the valuations of the individual sectional samples originally based on estimates of the contents of unsized concentrates under the microscope. For bores of about payable grade the correction to the columbite value was usually less than ± 5 percent. The $(NbTa)_2O_5$ content of columbite from the Younger Granites varies slightly. Bore values were expressed in terms of an arbitrary "shipping grade" containing 70 percent $(NbTa)_2O_5$.

To conform with the practice of this alluvial mining field, bore values were recorded in pounds per cubic yard. However, being based on the dry weight of the sample taken for concentration the recorded values are more strictly reproducible than those usually recorded in alluvial drilling practice. The latter are usually calculated with reference to either a shoe factor or a measured volume of partly disintegrated and more or less expanded core. In both cases the personal factor is variable and often considerable.

Determinations of bulk density and moisture content of the principal columbite-bearing decomposed granite indicated that the dry weight equivalent of a cubic yard in situ varied from 2,200 to 2,700 pounds. The figure 2,400 was used as a standard for the calculation of values per cubic yard from the laboratory sample valuation results.

When boring for valuation of reserves commenced there was no plant in existence which would indicate the percentage recovery which could be expected. It appeared certain however that recovery would vary appreciably with the grain size of the columbite. The average screen analysis of the columbite content of a representative number of samples from two payable areas are given in Table 7:

TABLE 7

B.S. sieve no.	Columbite content Block A %	Block B %
+ 25	0.5	4.5
+ 52	7.2	39.3
+ 72	10.7	17.6
+100	12.7	12.0
+150	19.6	9.7
−150	49.3	16.9

A commercial size pilot plant handling about 25,000 cubic yards a month has been in production since August 1953, and losses are now negligible down

to 170 B.S. mesh. Performance data for this plant based on screen and mineral analyses of samples made in the laboratory have indicated how the recovery of fines can be improved. Recovery should ultimately approach fairly closely to that of the desliming and superpanning technique used in the laboratory as the basis of valuing reserves.

RECOVERY OF PRIMARY COLUMBITE

Decomposed Rayfield-Gona Granite is soft enough to be mechanically excavated. The dumped material can be disintegrated with a monitor. In still water the slime settles rapidly but even slight turbulence will keep it in suspension. Suspended slime tends to carry fine columbite with it.

TABLE 8

DECOMPOSED RAYFIELD-GONA GRANITE
Average composition of 20 samples from Block A

Division		Percent	Free Columbite content	
			lb/ton	Distribution
Coarse sand	+52 B.S. mesh	35	1.2	7%
Fine sand	−52 B.S. mesh	15	35.5	93%
Slime		50	—	—

Analyses of Deslimed Sands

B.S. sieve no.	Percent	Columbite content	
		lb/ton	Distribution
+ 16	23.2	—	—
+ 25	22.0	0.2	0.5%
+ 52	22.3	3.9	7.2%
+ 72	6.7	21.9	10.7%
+100	4.9	32.7	12.7%
+150	6.0	40.5	19.6%
+170	2.5	45.7	8.9%
+240	3.9	44.7	13.1%
+300	3.3	43.1	11.2%
−300	5.2	36.7	16.1%

From where the pilot plant was erected, a representative number of samples were taken and analyzed in the laboratory to define the treatment problems. The results are given in Table 8.

On the basis of this analysis of the ore to be treated, recovery was visualized as requiring a low-cost solution to each of four problems.

Problem I. Separation of slime.
Problem II. Separation of coarse sand at about 52 B.S. mesh.
Problem III. Scavenging of relatively coarse columbite from deslimed low-grade coarse sand.
Problem IV. Recovery of fine columbite from deslimed high-grade sand.

These problems have now been largely solved in a pilot plant which incorporates hydrocyclones, jigs and tables. This plant recovers a mixture of the several heavy accessory minerals.

Comparisons of the percentage recovery of cassiterite, columbite and xenotime, the specific gravities of which are respectively 6.9, 5.5 and 4.7 show only a slight falling off in the finest grain sizes.

The heavy mineral concentrate from the recovery plant was trucked to a mineral dressing mill for further treatment. Here the columbite was extracted by magnetic separation and cassiterite recovered by gravity concentration. Electrostatic separation was used to remove non-conducting minerals reporting with both. The columbite which contained 76% $(NbTa)_2O_5$ was successfully dressed to a shipping grade of 68–70% $(NbTa)_2O_5$. Shipments of cassiterite were made at about 70% SnO_2.

In detail, however, many difficulties were encountered in the mineral dressing of the crude concentrate some of which have not yet been overcome. The difficulties arose mainly from overlapping in physical properties between two or more minerals. Intergrowths are also a problem, especially cassiterite in columbite and thorite in zircon. The specific gravities of the principal constituents, zircon, columbite and cassiterite, are sufficiently close for separation by gravity to be difficult without an excessive load of circulating middlings. The specific gravities of columbite, thorite and monazite are too close for gravity separation. The magnetic permeability of the columbite is overlapped by that of xenotime and part of the cassiterite and zircon. Electrostatic separation has so far not proved very effective. The facilities of the laboratory are now being switched to a study of the mineral dressing problems.

APPLICATION TO OTHER AREAS

The above methods of identification of granites in the decomposed state were developed for the Jos-Bukuru Complex, but they have since been successfully applied to several other areas on the Jos Plateau and to one off the Plateau.

The first task in each of these areas was to carry out a rapid geological reconnaissance, concentrating on the biotite granites. Without having to elucidate the age relationships and structures, it became only a matter of locating the columbite-rich granite and mapping its extent. This was greatly facilitated by the use of the aerial photographs which had been taken for Amalgamated Tin Mines of Nigeria Ltd. a few years previously. When the main areas of the columbite-rich granite were known, an outcrop geological map was prepared covering this granite and its immediate surroundings. This map provided the basis for more detailed work.

In this way large areas covered by the equivalents of the low grade to barren early biotite granites of the Jos-Bukuru Complex—the Jos and N'gell Granites—and the porphyries, could be subjected merely to sufficient examination to verify that they were not of economic interest for their columbite content. This procedure proved to be speedy and economical, as one geologist could cover a large territory, and no special prospecting equipment was required.

The reconnaissance procedure described above has been applied to the other areas of Younger Granite in varying degrees of detail.

Chief of these is the Ropp-Tenti Complex, situated about 20 miles south of the Jos-Bukuru Complex (Fig. 1). It covers an area of approximately 80 square miles. It is composed of rock types similar to those in the Jos-Bukuru Complex, but there are minor differences. Study was concentrated on one porphyry and on three of the biotite granites of which one, the Buka Bokwai Granite, proved to be the richest in columbite. These rocks are briefly described below.

Kwop Granite.—This has characteristics very similar to those in the Jos Granite. It contains large subhedral feldspars with some small inclusions of biotite. Quartz is anhedral, commonly in fairly large crystal aggregates, while biotite in places occurs in fairly large plates up to 1½ cm, a few in aggregations of very small crystals.

Gana Granite.—This is a medium-grained rock in which the feldspars vary considerably in size, orange when weathered, or whitish at times. Quartz is dull grey, anhedral, and it generally occurs in clusters. This granite may be compared with the N'gell Granite of the Jos-Bukuru Complex, but there are rather important differences, especially in the quartz type, described later.

Buka Bokwai Granite.—This rock can be compared with the Rayfield-Gona Granite of the Jos-Bukuru Complex. It has an even-grained sugary texture, and is a very distinctive type. The feldspars in all cases are composed of aggregates of very small crystals, which when weathered are white. The quartz is evenly distributed, in some cases in chains.

Yelwa-Balfour Granite Porphyry.—Several granite porphyries have been recognized in the Ropp-Tenti Complex. The Yelwa-Balfour Granite Porphyry is the principal porphyry in contact with the Buka Bokwai Granite. In the area in which we had occasion to map it, this rock is normally granitic in texture. It is a medium-grained rock with a very high proportion of darkish green feldspar, which is euhedral to subhedral. The quartz is bipyramidal, in places rounded. On weathering, this rock generally shows iron staining to a greater degree than the granites described above. It was named the Yelwa-Balfour Granite Porphyry by the Nigerian Geological Survey, who later mapped the Ropp-Tenti Complex in more detail, extending our economic reconnaissance.

Comparison of Quartz Types.—The quartz of the Kwop Granite is very similar to that of the Jos Granite, being composed of large bluish grains, roughly rounded, with secondary overgrowths. That of the Gana Granite is mainly composite, and also occurs in single, anhedral grains. It resembles the quartz of the N'gell Granite but differs from it in that it does not appear to be so chainy.

In the Buka Bokwai Granite the quartz is generally light grey and clear, but it may be fairly dark grey. It occurs as angular, generally single grains, but semi-composite grains are also present. The quartz grains are essentially equidimensional, but some tend to be chainy, and are very similar to those in the Rayfield-Gona Granite. The quartz of the Yelwa-Balfour Granite Porphyry is similar in general type to that of the Shen-Kuru Complex in the Jos-

Bukuru mass. It is typically bipyramidal in form, and the grains may look rounded in cross section due to corrosion of the edges.

It is seen from above that the characters of the quartz in the rocks of the Ropp area resemble those in the Jos-Bukuru Complex fairly closely. This made identification of the granites in the field comparatively easy, but the methods have been successfully applied to other areas in which local differences are more pronounced.

Mineralogy.—The mineralogy of the Ropp area is not known in as much detail as that of the Jos-Bukuru Complex, but the following are notes on each rock type, and a comparison with their equivalents in the Jos-Bukuru area. The heavy mineral assemblage in the Kwop Granite is much the same as in the Jos Granite. In the Gana Granite a pale brown translucent to subtranslucent zircon occurs, which resembles that in the N'gell Granite. The heavy mineral assemblage of the Buka Bokwai Granite compares closely with that of the Rayfield-Gona Granite. "Mud" zircon is the main typical mineral, but it is somewhat paler in color, and it appears to contain fewer columbite inclusions. A lemon yellow monazite appears to be more common than in the Rayfield-Gona Granite. Xenotime and thorite are also present, although they are not nearly as abundant as in the Rayfield-Gona Granite. Anatase is sometimes found, generally black and opaque, but occasionally green subtranslucent grains are found. They occur as octahedral or anhedral grains. Anatase is rather more widespread than in the Jos-Bukuru Complex. Columbite is generally well crystallized, but, as in the richer areas in the Rayfield-Gona Granite, it is maybe corroded, occurring as anhedral grains resembling coke. In the Yelwa-Balfour Granite Porphyry the zircon is typically prismatic, generally elongated, clear, colorless, and with a high lustre; it may contain inclusions. Ilmenite is common, but columbite is absent, as in all the granite porphyries.

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A. O. NIGERIA LIMITED,
P. O. JOS,
NORTHERN NIGERIA,
BRITISH WEST AFRICA.
March 1, 1956

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NATURE AND ORIGIN OF THE PYRITE DEPOSITS OF ST. LAWRENCE AND JEFFERSON COUNTIES, NEW YORK[1]

JOHN JAMES PRUCHA

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ABSTRACT

In St. Lawrence and Jefferson Counties, New York, there are 19 known occurrences of pyrite concentration of sufficient magnitude to warrant consideration as possible sources of sulfur. The important deposits occur in a belt about 35 miles long and three to four miles wide extending northeast from the vicinity of Antwerp. This belt lies within the Grenville Lowlands region of the northwest Adirondacks, southeast of the St. Lawrence River.

The bedrock is principally Precambrian Grenville metasediments and associated granitic rocks, but abundant small outliers of flat-lying Cambrian Potsdam sandstone occur throughout the region. The rocks of the isoclinally folded Grenville series have a marked foliate structure parallel to the northeast regional trend of the lithologic units and major folds, and generally dip northwest within the pyrite belt. The Grenville series is 15,000–16,000 feet thick in the Lowlands region.

The earliest pyrite mining in the region was in 1883–4 at the Stella mine; it ceased in 1921, at which time about 600,000 long tons of concentrates averaging about 40 percent sulfur had been produced.

[1] Published by permission of the Director, New York State Museum and Science Service, Journal Series No. 14.

Pyrite and lesser amounts of pyrrhotite are essentially the only sulfides present. The deposits occur in rusty-weathering pyritic gneisses, which are essentially chloritic and graphitic quartz-feldspar-mica gneisses containing more or less disseminated pyrite. The ore veins represent concentrations of pyrite within the rusty gneisses and occur as thin sheets parallel to the gneissic foliation. Thirteen analyses indicate a sulfur content from 20.2 to 35.6 percent, and average 25.6 percent sulfur.

The pyrite of the ores crystallized later than the gangue minerals, with the possible exception of sericite, and partially replaces them, chlorite being the most readily replaced. The graphite content of the ores characteristically parallels increases in the pyrite content.

The pyrite deposits are considered to be concentrations of iron sulfides formed from inherent constituents of the parent sediments from which the rusty gneisses were derived. It is believed that the parent sediments were argillaceous sandstones containing abundant organic impurities and some intercalated calcareous layers. The late-stage formation of abundant chlorite and the evident mobilization and recrystallization of sulfides and graphite well after the period of metamorphism are attributed to the circulation of aqueous solutions.

INTRODUCTION

THIS study of the pyrite deposits of St. Lawrence and Jefferson Counties, New York, was motivated by an acute world-wide shortage of sulfur at the start of the Korean War, and by the predicted continued disparity between world production and consumption in the next few decades. Shortly after this study began the immediate sulfur shortage was resolved by new production of brimstone on the Gulf Coast and by the conservation of by-product sulfur formerly wasted in smelting, oil refining, and other industrial processes. Future demands for sulfur, however, in the form of sulfuric acid will be greatly expanded as world populations increase and agrarian countries become progressively more industrialized. Increased use of commercial fertilizers to increase world food supplies will also necessitate much greater production of sulfuric acid.

It is the purpose here to describe the nature and occurrence of the pyrite deposits of St. Lawrence and Jefferson Counties, New York, and to discuss their origin. A later publication of the New York State Museum will contain detailed maps and descriptions of individual deposits and specific suggestions for exploratory drilling.

Location and Accessibility.—In St. Lawrence and Jefferson Counties there are 19 known occurrences of pyrite concentration of sufficient size to warrant consideration as possible sources of sulfur (Fig. 1). All of the more important deposits occur in an area about 35 miles long and three to four miles wide extending northeast from the vicinity of Antwerp and including parts of the Hammond, Antwerp, Gouverneur, Canton, and Russell quadrangles (Fig. 2). This area is about 25 miles southeast of the St. Lawrence River.

Scope of the Work.—Field work for this study began June 10, 1951, and continued until October 14, 1951. During July and August the writer was assisted in the field by Mr. Norman P. Cuppels. Field studies were completed during the last week in June and the months of July and August, 1952. In this second field season the writer was assisted by Mr. Arthur J. Richards.

Where possible, channel samples were cut on the more promising veins and analyzed for elemental sulfur content. The analyses were run by Mr. John A. Graham, of the New York State Geological Survey, using a gravimetric method with precipitation of sulfur as barium sulfate (9).

Plane table mapping on a scale of 400 feet to the inch was done on the more promising deposits. Maps of individual prospects will appear in a later publication of the New York State Museum. Reconnaissance mapping was done throughout the entire area in which the pyrite deposits occur.

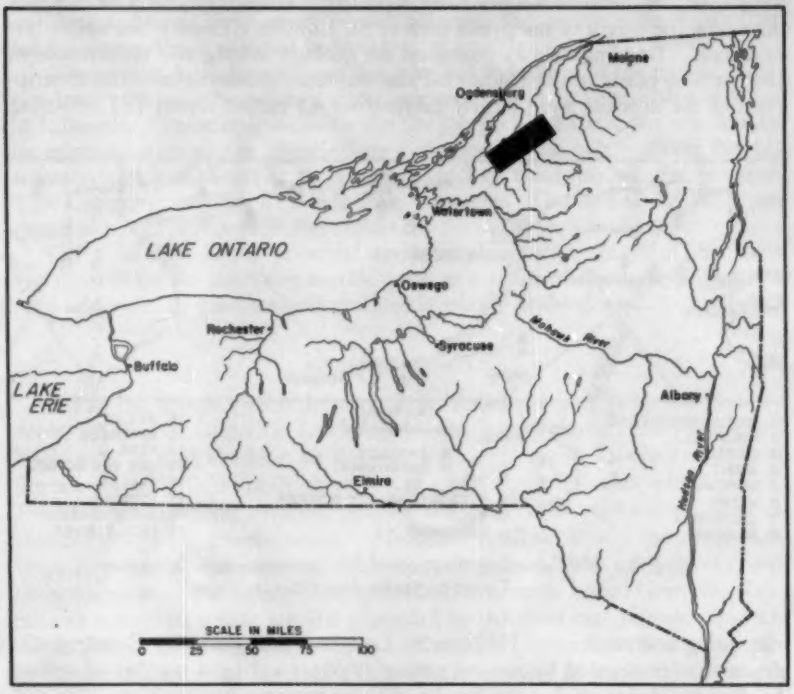

FIG. 1. Index map of New York State showing general area of the St. Lawrence and Jefferson Counties pyrite deposits.

During the course of the laboratory work 53 thin sections of the ores and associated rocks were studied in detail with the petrographic microscope. About 30 polished sections of the ores were prepared by the writer in the ore laboratory of the Department of Geology, Rutgers University, and studied in the petrography laboratory of the New York State Geological Survey.

Previous Work.—The first real attempt to understand the geology of the St. Lawrence and Jefferson Counties pyrite deposits was made by C. H.

Smyth, Jr. (20) who concerned himself primarily with the origin of the pyrite deposits. Martin (15) described the pyrite deposits of the Canton quadrangle and briefly discussed their origin from the point of view of field relationships. Buddington (2) made a brief study of the St. Lawrence and Jefferson Counties pyrite deposits principally to direct attention to the many undeveloped veins that were considered as possible sources of sulfur ore. His report proved of inestimable value in locating many of the pyrite localities in the course of the present study. Cushing and Newland (5) considered briefly the nature and distribution of the pyrite deposits within the Gouverneur quadrangle, but no detailed studies were reported. Miller (16) in a brief paper discussed the origin of the pyrite ores of St. Lawrence County but added few new data. Buddington (3) described the geologic setting and occurrences of the pyrite deposits in the Hammond and Antwerp quadrangles. His descriptions of the deposits were largely taken from his earlier report (2). During

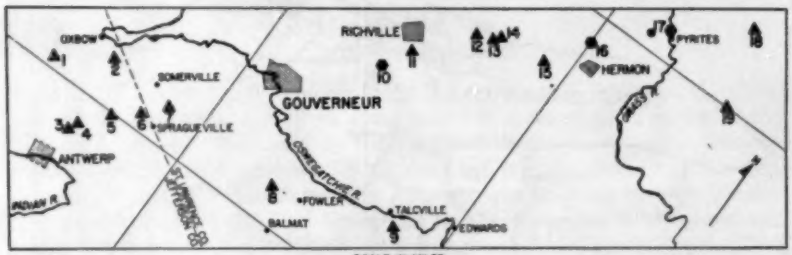

FIG. 2. Map showing location of St. Lawrence and Jefferson Counties pyrite deposits.

the spring and summer of 1951 the St. Lawrence and Jefferson County pyrite deposits were scouted by several geologists representing a number of sulfur-producing companies, but the results of these cursory investigations were not, of course, made public.

Geologic maps accompanying quadrangle geologic reports by Buddington (3), Cushing and Newland (5), Martin (15), and Dale (6) are helpful in orienting oneself to the regional geology.

GEOGRAPHY

The pyrite deposits of St. Lawrence and Jefferson Counties lie within the Grenville Lowlands region of the northwest Adirondacks, southeast of the St. Lawrence River. The region is characterized by northeast-trending ridges

and valleys of moderate relief which reflect differential erosion of strongly deformed metasedimentary rocks and granites. Elevations above sea level range from around 400 to about 800 feet, but local relief seldom exceeds 100 feet and commonly averages about half that.

The entire region has been glaciated, and the topography has been modified by abrasion and by deposition of glacial materials. Pre-glacial drainage has been greatly disrupted by drift so that swampy ground is common in the region. Principal streams, such as the Indian, Oswegatchie and Grass Rivers, emptying into the St. Lawrence, occupy channels that are a combination of pre- and post-glacial drainage courses. The cover of glacial sediments is not uniform, and over large areas the ice removed the mantle material and left behind scoured and polished bedrock.

Mining and dairy farming are the principal industries of the region. Zinc and lead, with some by-product silver, are mined at Balmat, and zinc is mined at Edwards. These operations by the St. Joseph Lead Company are situated on opposite ends of the 10-mile-long Gouverneur talc belt. Along the belt commercial talc is mined by the Gouverneur Talc Company, the International Talc Company, and the Reynolds Talc Company. Crushed stone, sand, and gravel are also produced in the region.

Dairy farming is the principal agricultural activity. Most of the farms are situated on the low-lying marble belts, and much of the more-rugged terrane underlain by gneisses and granites is wholly undeveloped.

REGIONAL GEOLOGY

All of the known pyrite deposits of St. Lawrence and Jefferson Counties occur within the Grenville Lowlands region lying between the Adirondack Highlands igneous complex on the southeast and the St. Lawrence River on the northwest. This low-lying region is a belt about 30 miles wide in which Precambrian Grenville metasediments and mixed rocks predominate over intimately associated granitic rocks. Abundant small outliers of flat-lying Cambrian Potsdam sandstone occur throughout the area. With a few local exceptions the rocks of the tightly compressed and isoclinally folded Grenville series possess a marked foliate structure parallel to the northeast regional trend of the lithologic units and major folds. The dips of the Grenville rocks progressively change from northwest through the vertical to southeast in passing from southeast to northwest. The Grenville series thus forms a great fan-shaped wedge lying between the large igneous complex of the Adirondack massif on the southeast and the granites of the Frontenac axis along the St. Lawrence River on the northwest.

The total thickness of the Grenville series in this region is probably in the neighborhood of 15,000–16,000 feet. In the absence of the usual criteria for ascertaining tops and bottoms of beds in this metamorphic terrane, there is some disagreement among workers as to top and bottom of the series. However, progressing from southeast to northwest across the Lowlands belt the sequence proposed by Engel and Engel (8) is as follows (generalized):

		Thickness in feet
Southeast	Biotitic quartz-microcline gneiss	500–1,000
	Marble (mostly dolomitic), with interlayered pyritic schists and feldspathic gneisses	4,000
	Quartz-biotite gneiss, largely migmatitic, with occasional interlayers of amphibolite and marble	2,800
	Marble, with some interlayered quartzite and feldspathic gneisses	4,000
Northwest	Complexly interlayered marble, quartzite and biotitic, feldspathic and pyroxenic gneisses	4,000

There are two general types of granite within the area. These are the Alexandria type, a medium-grained equigranular alaskite occurring as phacoliths; and the Hermon type, a medium- to coarse-grained rock ranging in texture from porphyritic granite to augen gneiss, with numerous local variations and grading locally into syenitic phases.

The granites of the region are all of Precambrian age. Most workers (5, 4, 7) consider the Alexandria type granite to be clearly of igneous origin. The Hermon type granite, however, is considered by Buddington (4), Engel and Engel (8), and others to be partly of magmatic origin and partly of replacement origin.

PYRITE DEPOSITS

History

The earliest recorded pyrite mining in the region was in 1883–4 at the Stella mine one mile north of Hermon, St. Lawrence County. With but few interruptions from that time until 1921, when all pyrite mining ceased in the region, one or more mines were active. Production from individual mines tended to be intermittent, and none of the mines was a large producer.

The failure of the active mines shortly after World War I can be blamed directly on the sudden depression in the sulfur market occasioned by the cutbacks in munitions and general industrial production following the armistice. Furthermore, during the war period production of Gulf Coast brimstone was tremendously increased, so that by 1919 production greatly exceeded market demand. In addition, producers of sulfuric acid were beginning to find that native sulfur not only cost less originally, but it was also less expensive to use in manufacture. Under these circumstances New York pyrite could no longer compete successfully with brimstone.

The Stella mine had the longest active history of any of the pyrite mines in the region. From its opening in 1883–84 until it was closed around 1920–21 it produced over half a million long tons of concentrates averaging 40–45 percent sulfur. Until 1885 the Stella mine was the only pyrite mine operating in the region. The production of this early period was shipped to Canada and Detroit, probably as rough concentrates, to be used for sulfuric acid manufacture. In 1900 the mine closed down because of the financial failure of its owners; and it remained idle until 1904, when it was sold to the St. Lawrence Pyrite Company. From that time until the end of World War I

the deposit was operated almost continuously, with production coming from several new shafts. In 1913 the St. Lawrence Pyrite Company was rated one of the four principal pyrite-mining companies in the United States (13). So far as is known, all of the company's production came from the Stella property. In 1951 the property was acquired by the General Chemical Division, Allied Chemical and Dye Corporation, but no new development work nas been initiated to date.

The Pyrites prospect (formerly referred to as High Falls) along the Grass River in and near the hamlet of Pyrites, about five miles south of the village of Canton, was first worked about 1886. Mining was carried on intermittently from that date until 1906, but production was small. The property was transferred in 1905 by McCray and Murphy, the original operators, to the National Pyrite Company of Canton. In 1907 the Oliver Iron Mining Company acquired the option on the property and conducted considerable exploration during the next year or so. A few hundred tons of ore were produced from a new shaft in 1907–8 and subjected to milling tests, although no large-scale mining was undertaken. The pyrite deposit is still owned by the Oliver Iron Mining Division, United States Steel Company, although no development work has been done since 1908.

The Cole mine, about five miles northeast of Gouverneur, was opened around 1900 by the Adirondack Pyrite Company. By 1905 it was the largest producer of pyrite in the region and shipped both raw ore and concentrates from its new mill. In 1906 the mine was taken over by the American Pyrites Company, but in 1907 the mill was dismantled and all work ceased. The mine was reactivated by the Hinckley Fiber Company in 1910. The output was used in the manufacture of sulfite pulp at the company's paper mill at Hinckley, N. Y. In 1915 the Cole mine once more became inactive when the Hinckley Fiber Company discontinued the use of pyrite in the manufacture of sulfite pulp. In 1916 the property was leased to the St. Lawrence Pyrite Company, which began dewatering the mine and carried on some exploratory drilling. Subsequently, in 1917, the property was taken over by the New York Pyrites Company, Inc., which continued to operate the mine until it was finally shut down in the early part of 1921.

Development work on other prospects took place at various times prior to 1920, with especial activity being noted for 1904 on the Stiles, Mitchell, Farr, and Hendricks properties; and for 1918 on the Dickson, Wight, Morgan, and Caledonia deposits.

Distribution

All of the more important prospects lie within a narrow belt extending 35 miles northeast from the vicinity of Antwerp. Three prospects (Kilburn, Pleasant Valley School, Little River) lie outside the three to four miles wide belt defined above (Fig. 2), but the deposits occur in rocks similar to those of the principal area. Many of the prospects are grouped into well-defined narrow belts within which the individual deposits are closely related geologically and geographically.

Production

Complete records of pyrite production in St. Lawrence and Jefferson Counties are not available. Three types of shipping products were produced —run-of-mine ore, selected and partially-cobbed lump ore, and concentrates— but the tonnages of each cannot be separately identified. The best evaluation the author can make indicates that the total production of all pyrite mines in the two counties during the period of active mining prior to 1921 was a little more than 600,000 long tons of concentrates, or equivalents, averaging about 40 percent elemental sulfur, of which the Stella property yielded around 500,000 tons, the Cole mine around 100,000 tons and all others around 20,000 tons.

General Character

The assemblage of ore minerals is exceedingly simple. Pyrite and pyrrhotite are essentially the only sulfides present, although traces of chalcopyrite and sphalerite have been noted in one or two instances. Arsenic sulfides are lacking. A very small amount of secondary hematite is the only metallic oxide found.

The pyrite of the ores is disseminated in a gangue of silicates characteristic of the rusty gneisses. Higher grade ore zones may include narrow veinlets and lenses of massive pyrite, but they constitute only minor parts of the mineralized zones. Where present, pyrrhotite occurs in the same manner as pyrite. The relative quantities of pyrite and pyrrhotite range widely from deposit to deposit. Pyrite is much more abundant than pyrrhotite generally speaking, but locally within a given deposit pyrrhotite may be the dominant sulfide. Both sulfides occur together in some of the veins, but characteristically grains of each do not occur intimately intermixed. Rather, the pyrite and pyrrhotite tend to occur in discrete veinlets or lenses. Graphite is a fairly abundant gangue mineral in all of the deposits.

The pyrite content of the typical rusty gneiss generally runs only about 5 to 10 percent by volume. The potential ore veins contain pyrite concentrations many times greater but grade laterally into ordinary rusty gneiss.

Thirteen of the most promising deposits were channel-sampled and analyzed for elemental sulfur content. It is believed that these analyses closely approximate the average tenor of the veins sampled, although acceptance of a lower-grade ore could greatly increase available tonnages. The deposits so sampled are: Oxbow Southwest, Gold Hill, Dickson, Wight, Morgan, Keene, Cole, Hendricks, Stiles, Mitchell, Farr, Pyrites, and Brick Chapel. The important Stella prospect was not channel-sampled because of the general inaccessibility of adequate thicknesses of the veins. Two grab samples of tailings at this locality and a grab sample taken at the Little River deposit were analyzed, however.

With the exception of the Stiles deposit, all analyses of channel samples indicate an elemental sulfur content in excess of 20 percent by weight, with a range of from 20.2 percent in the Oxbow Southwest prospect to 35.6 percent in the Gold Hill. The relatively poor Stiles deposit ran 15.2 percent elemental

sulfur. The weighted average of all samples analyzed is 25.6 percent sulfur. The results of the analyses are summarized in Table I.

Mode of Occurrence

The pyrite deposits of St. Lawrence and Jefferson Counties occur in distinctive rusty-weathering pyritic gneisses belonging to the Precambrian Grenville series of metasedimentary and mixed-rock formations. These so-called rusty gneisses are essentially chloritic and graphitic quartz-feldspar-mica gneisses containing more or less disseminated pyrite, with or without pyrrhotite, that has partially altered to hydrous iron oxides. Though comprising

TABLE I

SUMMARY OF CHEMICAL ANALYSES OF PYRITE SAMPLES

TABLE 1. SUMMARY OF CHEMICAL ANALYSES OF PYRITE SAMPLES

SAMPLE NO.	PROSPECT	TYPE OF SAMPLE	LENTH OF SAMPLE IN FEET	DIP OF VEIN	MINIMUM THICKNESS IN FEET OF VEIN WHERE SAMPLED	REMARKS	% SULFUR*
1–51	Oxbow Southwest	Channel	1.5	40°	8	From northern part	20.2
2–51	Oxbow Southwest	Channel	3.0	90°	15	Sheeted zone, southern part	29.4
3–51	Oxbow Southwest	Channel	2.5	90°	15	Sheeted zone, southern part	29.6
4–51	Gold Hill	Channel	1.7	35°	30	Lower pyrite band	35.6
5–51	Gold Hill	Channel	2.1	35°	15	Sheeted pyrrhotite zone	24.1
7–52	Dickson	Channel	27.0	20°	15	Flat-lying outcrop on vein	24.8
4–52	Wight	Channel	25.0	50°	30	Taken on vein in prospect pit	30.9
6–51	Morgan	Channel	6.0	45°	8	From vein in trench	23.5
8–52	Keene	Channel	4.5	35°	12	On vein	29.3
7–51	Cole	Channel	2.5	30°	3	2nd vein from top, at old shaft	29.3
8–51	Cole	Grab	—	—	—	Mill concentrates from open pile	36.5
3–52	Hendricks	Channel	3.0	65°	3	On vein	26.9
9–51	Stiles	Channel	5.0	40°	8	Wall of shaft portal	15.2
10–51	Mitchell	Channel	3.5	60°	5	Massive part of vein at shaft	28.3
11–51	Farr	Channel	3.7	90°	3	Cut obliquely across 3-foot vein in S.W. corner of shaft	30.6
1–52	Stella	Grab	—	—	—	Tailings from large pile near highway	1.5
2–52	Stella	Grab	—	—	—	Tailings from large pile near highway	2.8
6–52	Pyrites	Channel	8.8	55°	8	West bank of Grass River	22.9
9–52	Little River	Grab	—	15°	12	On vein in river bottom	19.3
5–52	Brick Chapel	Channel	9.0	27°	15	On vein, S.E. side of hill	26.2

*Analyses of all samples were run in duplicate. Sulfur percentage recorded is average of the two analyses in each case. Maximum deviation from average for a single analysis was 1.2% sulfur.

a relatively small part of the entire section, the rusty gneisses are nonetheless important and characteristic components of the Grenville series in the northwest Adirondacks. The rusty gneiss formations are comparatively thin but are notably persistent along the strike. In some cases thin bands of rusty gneiss less than 10 feet thick can be traced almost continuously for a mile or more. The rusty gneisses occur only within the major marble belts of the Grenville series but are closely associated with quartz-feldspar-biotite gneisses, thin-bedded quartzites, and amphibolites, as well as calcareous and dolomitic marbles. Locally the rusty gneisses are capped by Cambrian Potsdam sandstone, and in the Antwerp-Keene belt the pyritic gneisses grade upward into hematite ores lying below Potsdam sandstone caps. The rusty gneisses, in common with almost all gneisses of the region, have been abundantly injected

by granite and pegmatites. In the Stella and Pyrites deposits metagabbro is intimately associated with the rusty gneisses.

The rusty gneisses are strongly foliated, and individual micaceous layers commonly are highly schistose. In many places the rusty gneiss is strongly laminated, reflecting shifts in the ratios of constituent minerals from layer to layer. The inch-scale layering is particularly conspicuous where the gneiss contains thin interlayers of quartzite, which tend to stand out in positive relief on weathered surfaces. The color of the rusty gneisses in outcrop ranges from dark reddish brown to yellowish green. In places weathering has formed gossan to a depth of a foot or more. In all occurrences disseminated pyrite—and in places pyrrhotite—is conspicuous.

Thin section studies show the rusty gneisses to be composed principally of quartz, feldspar, mica, chlorite, pyrite, and graphite. Common minor constituents include hornblende, apatite, sphene, calcite, tremolite, epidote, clay minerals, garnet, tourmaline, and zircon. In some cases pyrrhotite instead of pyrite is the iron sulfide present. Commonly both minerals are present in a given deposit, but they rarely occur together in a single thin section. Microcline generally is the dominant feldspar, although sodic plagioclase may occur with the potash feldspar, and in a few cases is more abundant than microcline. The micas present include both muscovite and biotite, and possibly a little phlogopite. The ratios among the constituent minerals range widely from deposit to deposit, and from layer to layer within mappable units. Most commonly quartz is the dominant constituent and may comprise 50 percent or more of the rock. Feldspar, which generally is clouded with secondary clay minerals, commonly exceeds 30 percent by volume of the rusty gneisses. Chlorite, which replaces the micas and feldspars in large part, is generally a major constituent. Ordinarily the pyrite (and/or pyrrhotite) in the rusty gneisses does not exceed 5–10 percent of the rock by volume, but where concentrated into veins of potential ore it may be the dominant constituent. The veins are essentially loci of extreme concentration of pyrite within otherwise ordinary rusty gneisses. Such local concentrations of pyrite are generally correlative to exceptional concentrations of chlorite and graphite.

The ordinary rusty gneisses show a marked foliate texture in thin section. Most conspicuous are the thin elongate leaves of quartz oriented parallel to the foliation, and the similarly oriented blades of mica. Commonly the disseminated pyrite, too, is present as oriented elongate grains. These linear elements generally plunge northeast at angles of from 30 to 70 degrees. Where the pyrite is concentrated into veins of potential ore, however, the microscopic foliate textures generally are lacking and the textures are more uniform. Compositional banding within the ores nonetheless reflects the over-all foliation of the gneisses.

Structure of the Pyrite Veins

The Grenville rocks and their constituent rusty gneisses have all been subjected to severe regional stresses and metamorphism, and have been isoclinically folded and overturned toward the southeast so as to dip northwest at angles ranging from 20° to 90°. The pyrite veins occur as thin sheets

lying parallel to the foliation of the enclosing rusty gneisses. Locally the veins pinch and swell along the strike and down the dip so as to appear lenticular.

The veins appear to be very persistent along the strike and down the dip. At the Pyrites prospect, for example, the vein is exposed more or less continuously for a distance of six-tenth of a mile along the Grass River. McDonald (13) wrote that the upper vein at the Stella prospect extends 1,100 feet along the strike and had been worked to a depth of 900 feet down the dip. According to Buddington (2) the veins in the Anna shaft at the Stella prospect had been mined for 1,800 feet along the strike and were proved by diamond drilling to extend much further.

In at least six of the 19 deposits the pyrite mineralization occurs in zones of intense local folding and crumpling of the rusty gneiss, but it is not advocated that such local deformation provided a structural control of pyrite concentration. This viewpoint is more easily appreciated when it is understood that in more than two-thirds of the deposits no such local distortion is superimposed upon the regional structure and that similar local structures entirely devoid of pyrite mineralization are so common as to be characteristic of the Grenville rocks in general.

Mineralogy and Paragenesis

Pyrite.—This ore mineral, containing 53.4 percent sulfur by weight, occurs as disseminated grains, coarse knots, reticulating stringers, and cross-cutting dikelets in rusty gneiss gangue. Generally the disseminated pyrite is present as rounded and irregular grains, but locally there is a marked tendency toward euhedral development—especially where the pyrite has grown in a chlorite groundmass. The maximum diameter of individual grains ranges from fractions of a millimeter to more than eight centimeters. In most cases the pyrite is wholly recrystallized, but locally it may be severely broken along tiny crush zones.

The pyrite has crystallized later than all of the gangue minerals, with the possible exception of sericite, and partially replaces them. It penetrates along fractures and cleavages in the gangue minerals and forms characteristic "caries" replacement textures, but commonly there is a marked tendency for idiomorphic development of pyrite in replacement contacts. Pyrite also occurs interstitial to the gangue minerals, upon which it molds; and it commonly fills late fractures in the gangue. The pyrite appears to replace chlorite most readily of all the gangue minerals, or at least it is commonly most abundant in a chloritic groundmass and exhibits a very strong tendency toward idiomorphic development against the chlorite.

Many of the pyrite grains are seen in polished section to have narrow rims of hematite, which is presumed to be secondary after the pyrite. In a few grains studied the hematite was developed along minute fractures in the pyrite.

Pyrrhotite.—Pyrrhotite, which contains about 38.4 percent sulfur by weight, exhibits the same general relationship to the gangue minerals as does pyrite, except that it generally lacks the distinct granularity characteristic of

pyrite. Typically, the pyrrhotite occurs as very coarse, amoeboid grains replacing and cross-cutting the gangue minerals. As in the case of pyrite, the pyrrhotite is particularly abundant in chloritic groundmasses but lacks any idiomorphic development. A few discrete grains of hematite were noted in association with pyrrhotite in several polished sections, but no replacement rims of hematite on pyrrhotite were seen.

Hematite.—The hematite content of the ores is very low and averages somewhat less than one percent. For the most part it occurs as narrow replacement rims on pyrite grains. To a limited extent it occurs as scattered discrete grains in the ore but probably is wholly secondary after pyrite.

Graphite.—This mineral is relatively abundant in all of the ores. Characteristically, increases in graphite content parallel increases in pyrite content. The graphite, like the pyrite, has crystallized very late and replaces earlier gangue minerals in a manner quite similar to that of the pyrite. Characteristically the graphite occurs as blade-like aggregates of minute flakes, as highly irregular aggregates, and as thin rod-like stringers filling late cracks in the gangue. Graphite and pyrite appear to be essentially contemporaneous in final crystallization, and immediate geometric relationships between the two may indicate either one to have been slightly later than the other. For example, veinlets of graphite fill cross-fractures in pyrite; yet it is common for graphite to be wholly enclosed within pyrite. An interesting association of the two minerals is seen in a few euhedral grains of pyrite bounded on all sides by narrow tabular borders of graphite. In a few instances a very narrow zone of chlorite or muscovite was seen to lie between the pyrite and the bordering graphite, all of which strongly suggests differential replacement of some earlier zoned silicate grain.

Chlorite.—A light green chlorite is abundant in all of the ores and associated rusty gneisses. Typically it occurs as fine-grained aggregates replacing all of the gangue silicates, but it is especially abundant as a replacement of biotite, feldspar, and hornblende. Commonly it forms vein-like aggregates filling late fractures cutting across all other minerals, including pyrite, and it is abundant interstitial to the other gangue minerals. Veinlets of chlorite filling fractures crossing earlier chlorite aggregates, as seen in occasional thin sections, indicate ready mobility of the chlorite up to the latest stage of crystallization.

Feldspar.—Microcline is the most abundant feldspar in the gangue. Commonly it is the only feldspar present in a given thin section of ore, but in other cases it occurs along with minor orthoclase and sodic plagioclase. Almost without exception the potash feldspars are at least partially altered to clay minerals and perhaps sericite, and commonly individual grains are altered almost beyond recognition. In a few sections studied the dominant feldspar was sodic plagioclase, in part anti-perthitic. The plagioclase too is highly altered, and commonly chloritized, so that a precise determination of the anorthite content could not be made.

Hornblende and Biotite.—These two mafic minerals constitute only a minor part of the ore—seldom more than five percent by volume. The biotite, in part at least, is secondary after hornblende; and both minerals typically are

largely altered to chlorite. It seems probable that prior to chloritization hornblende and biotite were major constituents of the gangue.

Miscellaneous Gangue Minerals.—These include the common minor constituents of the typical rusty gneisses: apatite, sphene, calcite, tremolite, epidote, clay minerals, garnet, tourmaline, zircon. The calcite and tremolite reflect inherent calcareous zones in the parent rusty gneisses. Locally a little calcite appears to have mobilized and recrystallized very late to form minute fracture-filling and interstitial veinlets. The small amount of epidote present is secondary after plagioclase. The clay minerals result from alteration of both feldspars. At least some of the tourmaline was probably introduced by the granitic solutions that have injected the pyritic gneisses locally. The derivation of the apatite, sphene, garnet, and zircon is uncertain.

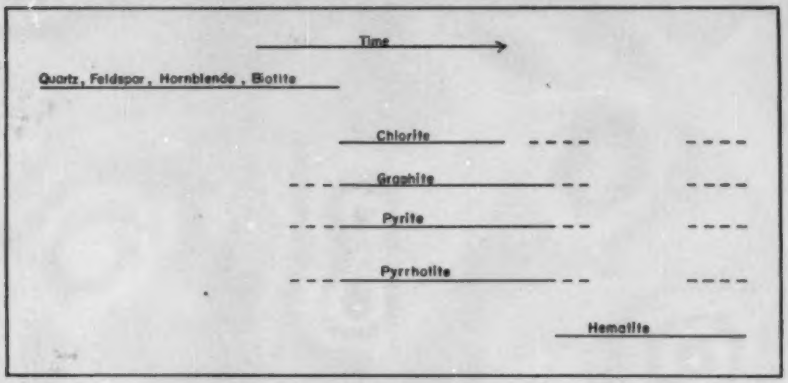

FIG. 3. Diagram showing sequence of final crystallization of the principal minerals in the pyrite deposits of St. Lawrence and Jefferson Counties, New York.

Paragenesis.—The sequence of final crystallization of the principal minerals in the ores is summarized in Fig. 3. Textural relationships between the various minerals are shown in Figures 4–11.

ORIGIN OF THE PYRITE DEPOSITS

The problem of the origin of the pyrite deposits of St. Lawrence and Jefferson Counties is a complex one for which no unequivocal solution has been worked out. Clearly the genesis of the pyrite deposits is closely related to the problem of origin of the rusty gneisses in which they occur; but though several hypotheses may be developed which are compatible with all of the factual data in hand, the final interpretation depends in large measure upon the relative importance subjectively accorded the various factors involved. The complexity of the problem was well appreciated by Smyth (20), whose study exposed the many facets meriting consideration; his principal conclusions will be reiterated in this report.

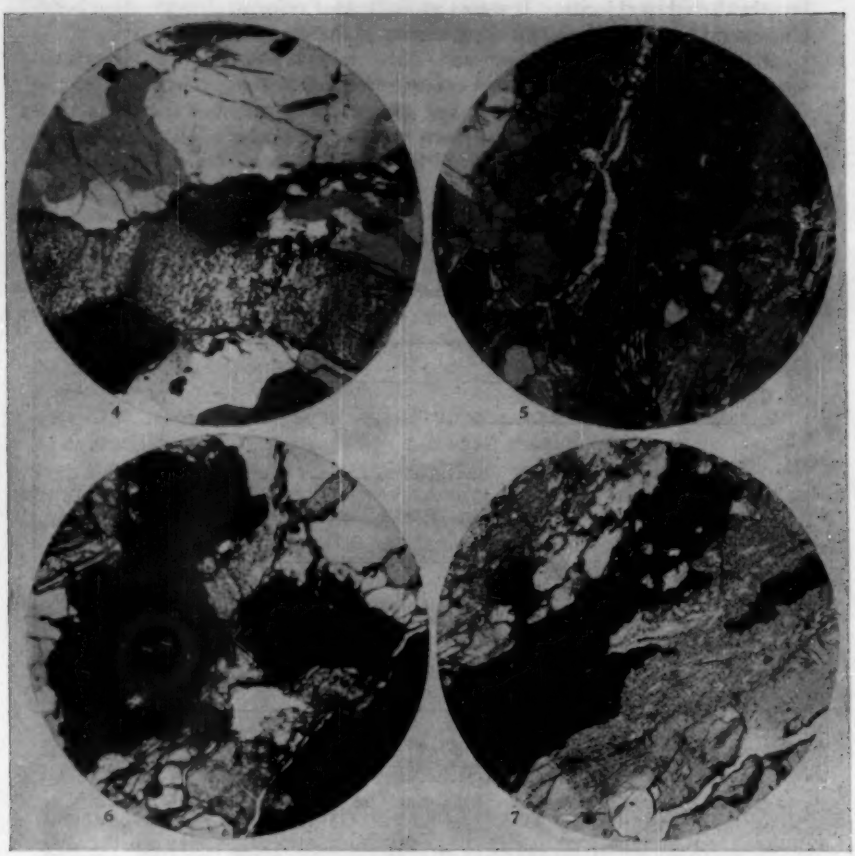

FIG. 4. Photomicrograph of pyritic rusty gneiss from portal of southern shaft at Pyrites prospect showing late chlorite veinlet cutting across pyrite (black), quartz, and feldspar. X-nicols. × 110.

FIG. 5. Photomicrograph of rusty gneiss from outcrop on right bank of Grass River above lower bridge at Pyrites showing chlorite veinlets (c) cutting across quartz and chloritized feldspar and biotite. Note veinlet of later quartz cutting across chlorite veinlet on right edge of field. X-nicols. × 110.

FIG. 6. Photomicrograph of pyrite ore from portal of shaft at the Stiles prospect showing idiomorphic development of pyrite (black) in gangue of quartz (white) and chloritized feldspar and biotite. White partial rims on pyrite in right half of field are quartz. Nicols partly crossed. × 110.

FIG. 7. Photomicrograph of pyritic rusty gneiss from outcrops in bank of Elm Creek at Stella prospect showing irregular grains of pyrite replacing gangue of quartz (white) and highly chloritized feldspar and biotite. Ordinary light. × 110.

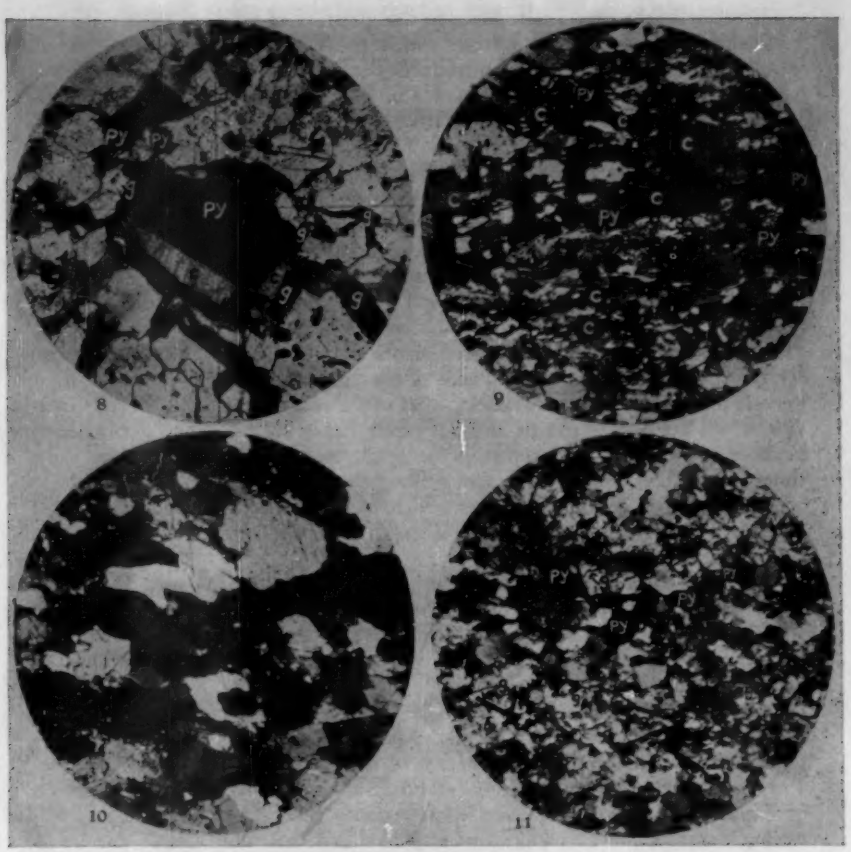

FIG. 8. Photomicrograph of pyritic rusty gneiss from Kilburn prospect showing pyrite (py) partially rimmed by chlorite (c) and graphite (g) in a manner suggesting selective replacement of a zoned crystal. Note abundant graphite and chlorite. × 110.

FIG. 9. Photographic projection of thin section of schistose rusty gneiss from Stiles prospect showing irregular grains of pyrite (py) in strongly foliated, chloritized (c) matrix. Clear grains are mostly quartz. X-polaroids. × 15.

FIG. 10. Photographic projection of thin section of rusty gneiss from the A vein at the Stella prospect. The irregular opaque grains are pyrrhotite. X-polaroids. × 15.

FIG. 11. Photographic projection of thin section of pyritic rusty gneiss from the Keene prospect showing irregular grains of pyrite (py) and short stringers of graphite (g) in a slightly chloritized matrix of quartz and feldspar. X-polaroids. × 15.

Essentially the problem reduces to the question of whether the pyrite was indigenous to the sediments from which the rusty gneisses were derived, whether it was hydrothermally introduced, or whether it resulted from chemical combination of original components of the rusty gneisses with hydrothermally introduced elements. Lack of precise knowledge of the physico-chemical conditions under which the pyrite was formed or recrystallized makes impossible positive evaluation of the various possibilities at this time.

The present writer, taking full cognizance of the mineral assemblages involved and the specific characteristics of individual occurrences, will attempt to evaluate the problem in terms of the regional geology. The marked similarity of all the deposits demands an interpretation which will fit all cases.

Previous Interpretations.—Newland (17) drew a close parallel between the pyrite deposits and the magnetite deposits of the northwest Adirondacks. He stated, "Though inclosed by sediments the . . .[pyrite]. . . deposits can scarcely be construed as original beds of contemporaneous formation, but their genesis probably has been parallel to that of the magnetites found in the Grenville which are always pyritic and not rarely richly so. . . . The pyrite seems to have impregnated and replaced the schist to a great extent, at the same time filling small fissures and seams along the bedding planes. Its origin is traceable to iron-bearing solutions which have circulated through the schist when it was probably at considerable depth from the surface and perhaps in a less metamorphosed condition."

Smyth (20) proposed a complex origin for the pyrite deposits. He stated, "In summing the matter up on the basis of present data, it appears to the writer that four periods of pyrite formation are probable: 1, A primary precipitation of pyrite contemporaneous with the formation of the sediments; 2, a concentration of this pyrite by circulating ground waters, with the addition, perhaps, of pyrite of deep-seated origin, before the period of metamorphism; 3, but of minor importance, a recrystallization of all pyrite, accompanied perhaps by a certain amount of formation of new pyrite during metamorphism; 4, a further development and concentration of pyrite by magmatic agencies, perhaps working in combination with groundwaters, as outlined above, following the period of active igneous intrusion and metamorphism."

Smyth (20) attempted an evaluation of the relative importance of each of the four periods proposed: "While, on the assumption that the four periods of concentration are well established, there is still room for much difference of opinion as to their relative importance. From what has been said above it is evident that the writer regards original sedimentation as merely of potential importance affording only disseminated pyrite which would demand great concentration to be available. Such concentration may have been effected to a considerable degree in the hypothetical second or ground-water period, was probably not greatly influenced in the third or metamorphic period, and was chiefly accomplished in the fourth or postmetamorphic period, during which minerals formed in the third or metamorphic period were broken down and replaced by others, of which pyrite is the most important. That much of the pyrite was actually deposited in its present form and place during this period is certain; that the ore bodies are to a large degree the products

of this deposition is the conclusion reached from the evidence now available."

Martin (15) concluded from his study of the field relations of the pyrite occurrence at Pyrites that the pyrite was primarily of sedimentary origin, and that igneous effects, if indeed there were any at all, were limited to the reconcentration of material already a constituent of the rusty gneisses.

Miller (16) concluded that the principal source of the pyrite was the Grenville rusty gneisses themselves rather than cooling magma. According to his view, initially disseminated pyrite in the rusty gneisses was taken into solution by the penetrating liquids and vapors from granites and pegmatites and carried to higher levels to be redeposited in more concentrated form.

Buddington (4), and Leonard (12) believe that the pyrite deposits are of hydrothermal replacement origin. They point out that the distribution of the pyrite deposits fits into the zonal arrangement of Adirondack mineral deposits and suggest that they represent the low-temperature phase of replacement by hypogene ore carriers spreading outward from the core of the Adirondacks.

Engel and Engel (8), in referring to the schistose rusty gneisses containing the Kilburn prospect, conclude that the pyrite largely is indigenous to the parent sediment. They state: "The pyritic, graphitic schist undoubtedly has evolved from an argillaceous and somewhat calcareous sandstone, which may have contained much of the iron and sulfur combined in the pyrite as sedimentary or diagenetic constituents."

Present Interpretation.—The writer tentatively considers the pyrite deposits of St. Lawrence and Jefferson Counties to be concentrations of iron sulfides formed from inherent constituents of the parent sediments from which the rusty gneisses were derived. The exact character of the original sediments can only be a matter of speculation, for they have been thoroughly recrystallized during regional metamorphism and modified by the granitic solutions that moved through all of the Grenville rocks in the region. However, it seems likely that the parent sediments were argillaceous sandstones containing abundant organic impurities and some intercalated calcareous layers. The late-stage formation of abundant chlorite and the evident mobilization and recrystallization of sulfides and graphite well after the period of metamorphism are attributed to the late circulation of aqueous solutions which pervaded the entire region.

A number of considerations militate against the interpretation of the pyrite deposits being of hypogene origin. In the first place the complete relegation of the deposits to a particular rock type—the rusty gneisses—strongly suggests a sedimentary or diagenetic origin for the iron sulfides. The pyritic rusty gneisses occur as indigenous formations of the Grenville series and clearly represent a characteristic metasedimentary type interlayered with typical Grenville marbles and paragneisses. The rusty gneisses are not restricted to a single horizon, but they are restricted to the major marble belts and appear to represent a phase of sedimentation marking the shift from clastic to chemical sediments. Hence, the rusty gneisses lie close to the contacts between the marble belts and the quartzose-feldspathic gneisses. Individual layers of rusty gneiss only a few feet thick intercalated with marbles and related metasedi-

ments commonly can be traced for thousands of feet along the strike and locally serve as reliable horizon markers, yet lithologically they are remarkably uniform throughout and the iron sulfides are wholly confined to them. Contacts between the rusty gneisses and other closely associated metasediments typically are sharp, and local cross-veining of the rusty gneisses by apparently remobilized sulfides is strictly intraformational. The writer believes that any such precise stratigraphic selectivity by sulfide-bearing hypogene solutions is improbable.

The simplicity of the sulfide mineral assemblage in the rusty gneisses and associated pyrite deposits also casts serious doubt on the idea that the iron sulfides represent the low-temperature phase of replacement by hypogene ore carriers spreading outward from the core of the Adirondacks. The Kilburn and Pleasant Valley School prospects occur within a few thousand feet stratigraphically of the mineralized zones of the Balmat, Hyatt, and Edwards mines of the Edwards zinc belt, and they surely occupy approximately the same temperature zone as that of the zinc mines. Yet the sulfides of the rusty gneisses consist of only pyrite and pyrrhotite in significant amounts. The galena, abundant sphalerite, and minor chalcopyrite and barite of the Balmat, Hyatt, and Edwards mines are lacking in the pyrite deposits of the rusty gneisses. Brown (1) points out that the pyrite of the zinc ores in the Edwards district was the earliest of the ore minerals to form, although some possibly continued to form in decreasing amounts throughout most of the period of sulfide deposition. It becomes difficult, then, to consider the sulfides of the rusty gneisses as lower-temperature, and possibly later, hypogene minerals—especially since there is no evidence in the zinc mines for such a period of pyrite-pyrrhotite mineralization. The occurrence of abundant iron sulfides in the quartzose-feldspathic rusty gneisses is at complete variance with the marked tendency of the pyrite and other sulfides of the zinc deposits to replace moderately silicated marbles.

A further line of evidence strengthens the case against the rusty gneiss pyrite deposits being of hypogene origin. The belt of rusty gneiss containing the old pyrite workings at Pyrites appears to be wholly enclosed in metagabbro and is considered to be a xenolith caught up by gabbro magma which invaded the Grenville rocks. The rusty gneiss and related pyrite is wholly typical of similar rock types considered in this report. There is no evidence that late sulfide-bearing solutions passed through the metagabbro to deposit pyrite and pyrrhotite in the gneiss xenolith. The metagabbro contains only traces of accessory pyrite, as do most of the rocks of the region. Smyth (20) pointed to the improbability of the gabbro being the source of sulfide-bearing solutions. It thus appears that the sulfide material of the rusty gneiss band at Pyrites must have been part of the gneiss before the gneiss was engulfed by the gabbro, although the local concentration and recrystallization of the sulfides may have been much later. Similarly, metasedimentary rocks closely associated with rusty gneisses elsewhere in the region appear to be wholly unaffected by sulfide-bearing solutions which would surely have had to pass through them if such solutions were to account for the formation of the pyrite deposits.

Of particular significance is the abundance of graphite in all of the rusty gneisses, and the marked parallelism between pyrite and graphite in regard to local concentration of each. Practically all of the Grenville metasediments contain at least traces of flake graphite, but the graphite content of the rusty gneisses is exceptionally high and almost certainly reflects abundant carbonaceous material in the original sediments.

The development of iron sulfides in marine sediments rich in organic matter is well known. Under reducing conditions hydrogen sulfide (H_2S) can be produced by bacterial action on sulfur-bearing organic compounds, and the presence of hydrogen sulfide may cause precipitation of iron sulfides. Rankama and Sahama (19) indicate that in such reactions ferrous sulfide is considered to be the precursor of pyrite, and they point out that such rocks may also contain pyrrhotite and other sulfides.

According to Marmo and Mikkola (14), who describe the carbonaceous sulfide-bearing schists (Precambrian) of Finland, either pyrite or pyrrhotite may form by the recrystallization of authigenic ferrous sulfide, depending upon the partial pressure of sulfur during the recrystallization. Pyrrhotite is considered to form according to this equation:

1. $$Fe(OH)_2 + H_2S = FeS + 2H_2O.^1$$

However, if the partial pressure of sulfur is great enough pyrite will form by this reaction:

2. $$Fe(OH)_2 + H_2S + S = FeS_2 + 2H_2O.$$

According to Vayrynen (21), if the concentration of hydrogen becomes strong enough the concentration of sulfur will decrease concurrently according to the following equation.

3. $$\frac{S}{4} = \frac{k}{2^2} \cdot \frac{(H_2S)}{(H)^2}.$$

The reaction rate will then increase in favor of equation 1 and replacement of pyrite by pyrrhotite is possible.

Thus it may be that at least some of the pyrrhotite in the rusty gneisses is a replacement of earlier pyrite, but the significant point is that pyrrhotite is not necessarily a product of high-temperature hypogene solutions.

Galliher (10) states that the iron sulfide content of marine black muds seldom exceeds two percent. Gilbert (11), however, points out that many of the Precambrian black slates and graywackes of the Lake Superior region are highly pyritic, and he mentions black graphitic slates in the Iron River district in Michigan containing as much as 40 percent authigenic pyrite.

Petrographic evidence is abundant that aqueous solutions were plentiful in the rusty gneisses during the period of final crystallization of the pyrite and associated pyrrhotite and graphite. The abundant secondary development of

[1] The formula of pyrrhotite is given simply as FeS to facilitate balancing the equation.

hydrous minerals such as biotite, chlorite, clay minerals and muscovite or sericite penecontemporaneously with the pyrite establishes this point beyond reasonable doubt. The exact composition of the aqueous solutions is not known, of course; but there is little doubt that wholly within the rusty gneiss formations they facilitated the mobilization, concentration, and recrystallization of the pyrite and graphite, in addition to contributing to the formation of hydrous secondary minerals. The ready mobility of both pyrite and graphite under similar conditions is well established.

The abundant development of chlorite, so characteristic of the rusty gneisses, is not understood. Clearly the chemical environment producing the chlorite was distinctly different from that in all other paragneisses of the Grenville in the region; for in no other rock type is chlorite so abundantly developed, yet all of the Grenville paragneisses show evidence of secondary formation of hydrous minerals. Tentatively the writer must beg the question and agree with Smyth (20) that the chloritization ". . . appears to be the result of unusually potent chemical agents associated with the formation of pyrite."

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NOTES ON THE GEOTECTONICS AND URANIUM MINERALIZATION IN THE NORTHERN PART OF THE NORTHERN TERRITORY, AUSTRALIA

J. RADE

ABSTRACT

An attempt is made to connect the uranium mineralization in the northern part of the Northern Territory with the geotectonics, by applying the geotectonic theories of Kraus. The bathyrheal underflow is responsible for the horizontal movements of the separate massifs in the eastern part of the Pine Creek Orogen. Strike shearing that occurred along anticlines between the massifs cut the Pine Creek Orogen into longitudinal slices, which were then cut by northeast trending faults, along which further horizontal movements occurred. The presence of these two sets of faults facilitated the curving of the eastern part of the Orogen towards the northeast by the bathyrheal underflow. This curving of the Orogen initiated a couple in the area to the east of it, where structurally weak zones have permitted the extrusion of lava. The uranium mineralization favored these structurally weak zones, the sheared anticlines and the transverse faults because of the deep-seated character of these features.

INTRODUCTION

THIS paper deals with an area in the northern part of the Northern Territory extending from 130½° E to 132½° E and 12½° S to 14½° S. It comprises about 11,221 square miles. A knowledge of its geological structure is of practical importance because important uranium deposits occur here. The author's intensive search for uranium deposits and geotectonic studies have revealed interesting controlling structures, which will be described in this paper. The associated uranium mineralization will also be considered briefly.

Previous literature concerning the geology and economic mineral deposits of the area includes several reports of the Aerial Geological and Geophysical Survey of Northern Australia, and papers by Fisher and Sullivan (4), Hossfeld (5), Noakes (14, 15), Sullivan (18, 19), Sullivan and Iten (20), Sullivan and Matheson (21) and Voisey (22).

GENERAL GEOLOGY

The area is occupied mainly by rocks of the Lower Proterozoic Brock's Creek Group, which consist of siltstones, sandstones, conglomerates and tuffs (14). These deposits were folded and intruded by granite at the end of the Lower Proterozoic.

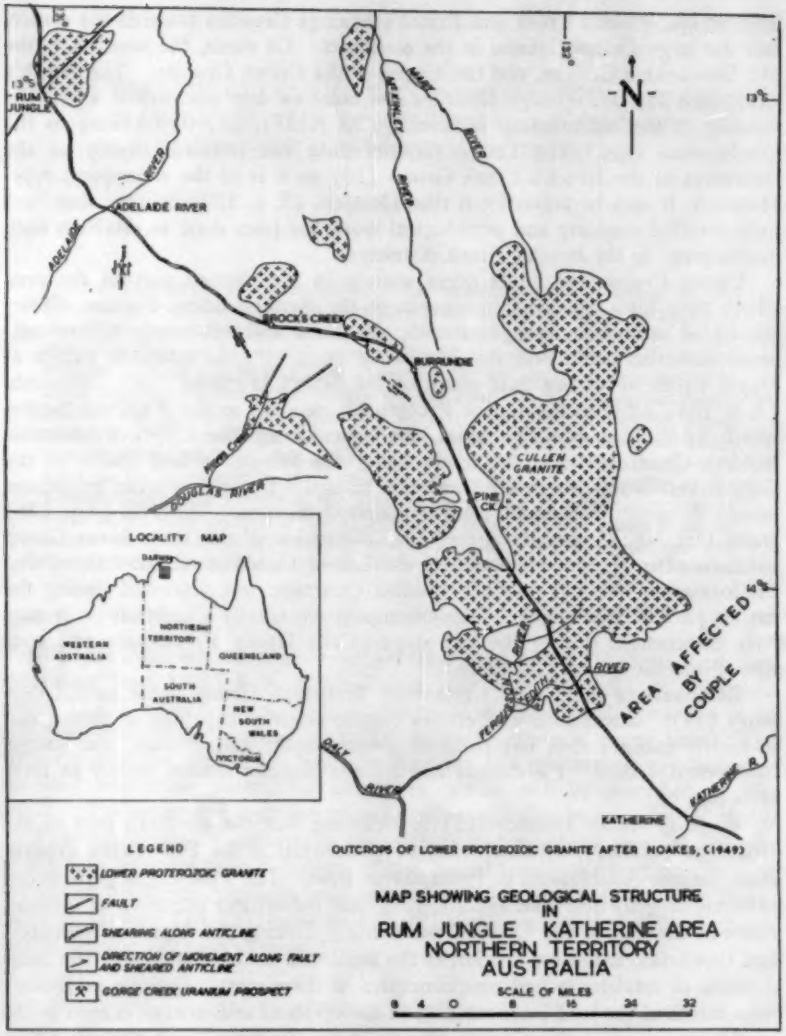
Several outcrops of granite occur, arranged more or less diagonally across the area. The Rum Jungle Granite is in the extreme northwest, with the Mt.

Shoobridge, Brock's Creek and Prince's Springs Granites towards the centre, and the large Cullen Granite in the southeast. Of these, the smallest is the Mt. Shoobridge Granite, and the largest is the Cullen Granite. The Brock's Creek and Mt. Shoobridge Granites are more or less concordant with the bedding of the surrounding sediments (20, p. 17), i.e., they belong to the synchronous type. The Cullen Granite does not conform closely to the structures of the Brock's Creek Group (14) so it is of the subsequent type. However, it may be pointed out that Hossfeld (5, p. 120) believes that "too little detailed mapping and petrological work has been done to establish such distinctions" in the Brock's Creek district.

Upper Proterozoic rocks occur mainly in the eastern part of the area where they form the western margin of the Arnhem Land Plateau. They consist of sandstones, conglomerates, siltstones and volcanics. Other outcrops occur scattered over the rest of the area, e.g., the infaulted outlier at Hayes Creek about one mile south of the Stuart Highway (14). Hossfeld (5, p. 135) includes the Upper Proterozoic deposits in the Buldivan Series, which he divides into two units, the lower being the Upper Proterozoic Buldiva Quartzites, and the upper being the limestones and shales of the Daly River Group which are Cambrian in age. These Cambrian limestones occupy the southwestern and southern parts of the area. Hossfeld (5, p. 136) states that "it is generally agreed that deposition of the Daly River Group commenced in the upper portion of the Lower Cambrian and it follows that the formation which is now the Buldiva Quartzite was deposited during the earlier part of that epoch. Deposition may be wholly Cambrian or it may have commenced during the last stage of the Upper Proterozoic and continued into the Lower Cambrian."

Remnants of the Lower Cretaceous Mullaman Group occur as hill cappings (14). Small areas of Tertiary laterite occur as cappings on mesas, and in higher country that has suffered greater uplift and erosion, the laterite has been dissected. Pleistocene and Recent deposits consist mainly of river alluvium.

We may follow Hossfeld (5) in believing that the northern part of the Northern Territory, which Noakes (15) included in the Pine Creek geosyncline, became consolidated in Precambrian time. The Pine Creek geosyncline suffered orogeny and both synorogenetic and subsequent intrusion of plutonic rocks at the end of the Lower Proterozoic. During the Upper Proterozoic and Cambrian, extensive erosion of the mountain chains resulted in the large deposits of sandstones and conglomerates of these ages. Definite oscillatory movements of the land mass resulted in the cycles of sedimentation seen in the sandstones, e.g., on the western margin of the Arnhem Land Plateau where they are typically developed (see later in this paper). It must be remembered that this part of the Northern Territory was consolidated during the Precambrian. It suffered no intense orogenic movements after the Lower Proterozoic orogeny. The area was able to respond only slightly to later orogenic forces, and consequently only germanotype tectonics have resulted. Monoclinal folding, commonly associated with this type of tectonic, is found



in the eastern part of the area where faulting is especially severe. Not only here, but throughout the northern part of the Northern Territory there has been severe faulting. Block faulting, which is typical of such early consolidated regions, is common. Marginal block faulting with monoclinal folds and steep dips has previously been observed on the north coast of Arnhem Land by Fairbridge (3, p. 17), Brown (1) and Jensen (6).

Although the area was not affected by violent orogenic movements, it responded gradually to movements of crustal blocks caused by a deep seated regional underflow of geoplasma (see below). The crustal blocks were moved horizontally by the underflow, causing shearing on a regional scale in the overlying rocks.

The sequence of magmatic evolution that can be observed in the area is of interest from a geotectonic point of view. Bubnoff (2) states that the delineation of the large crustal blocks of the world is much more precise when based on magmatic evolution than when based on tectonics alone. Stille (17) has stressed that vulcanism is very closely associated with orogenic cycles, and he distinguishes several cycles of vulcanism that occur in the geotectonic evolution of the world. One of the types he distinguishes is subsequent vulcanism that is post-orogenetic. The main magmatic cycles observed in the area under consideration are synorogenetic and subsequent plutonism associated with the epi-Lower Proterozoic orogeny, and extrusion of acid and basic lavas in the east of the area at the close of the Precambrian. The latter vulcanism is of the subsequent type.

After this brief review of the geotectonic processes involved the resulting structural features of the area may now be considered.

STRUCTURAL FEATURES

Three types of structures that are highly characteristic of this part of Australia are found. They are of economic interest since they are closely related to the uranium mineralization. They are:

1) Shearing along anticlines, found mainly in the central part of the area in rocks of the Lower Proterozoic Brock's Creek Group. A typical example is the George Creek Uranium Prospect, found by the author in 1954. It is situated 63 miles SSE of Darwin and 8 miles south of Adelaide River on the side of an anticline in greywackes and siltstones of the Brock's Creek Group. The anticline has been sheared along its length, the east side moving north and the west side south. Tension fractures are also present, and the uranium mineralization is located in these, and also in the siltstones where there has been some replacement of beds. Other examples are the Adelaide River Uranium Prospect 57 miles SSE of Darwin, and the Burrundie Uranium Prospect 95 miles SE of Darwin and 3¾ miles SW of Burrundie railway siding, where the mineralization is associated with recurring movements in an originally strike-sheared and transversely fractured anticline.

2) Couples applied to comparatively large areas, e.g., the area north of Katherine, where Upper Proterozoic and Lower Cambrian sandstones and volcanics have been broken into ENE trending slices by the action of a couple. The couple arose from the movements of two rigid masses, the Cullen Granite on the west and another mass of igneous rocks on the east.

3) Horizontal movements along northeast trending faults, which affect both of the previously mentioned structures. Such movements are widespread, but are especially marked in the west of the area. The direction

of movement has been such that the NW sides have moved to the NE and the SE sides to the SW. The greatest horizontal movement is 3¼ miles along the Giant Fault which dissects the Rum Jungle Granite (21, p. 752). In the area north of Katherine the faults of this type are tension faults of regional importance, but the movements along them are far smaller than those at Rum Jungle. At Burrundie the displacements were very small. Throughout the area the uranium mineralization favoured these northeast trending faults.

The geotectonic theories of Kraus (7, 8, 9, 10, 11, 12, 13) can be applied with considerable success to this region. Kraus divides orogen formation into several phases as follows:

1. Deep Orogenic (Hyporogenic) Phase. This phase commences with slow movements in the geosyncline directed towards the bottom. Great thicknesses of strata of pelagic and deep-sea facies are characteristic of this phase. Then the sea floor commences to form rises and troughs, and the facies and relief-types of an archipelago-sea are developed. Folding follows with compression of the bottom, the compressed portion ascending to a higher level. The direction of movement in the originating orogen is from the center outwards.

2. High Orogenic (Epiorogenic) Phase. In this phase the high relief and the molasse are originated.

3. Continental End-phase. Characterized by the consolidation of the orogen with the adjacent continent.

Kraus points out that two factors are involved in the formation of an orogen. These are:

1. The sinking tendency coupled with folding and sliding of the sinking rock mass. This happens in the hyporheon.

2. Horizontal tension of the earth's crust. This tension is originated deep under the hyporheon in the bathyrheon by flowing geoplasma.

After the orogenic phases the orogen commences to break in pieces as a result of the regional tension to which it becomes subject. The center of the orogen is the most unstable part and is the first affected by tensional forces, breaking along its length into deep-seated median fissures ("Narbenschnitte") which represent the weakest zones of the orogen. Thus graben-depressions originate in the center of an orogen subject to regional tensional stresses. Generally portions of the orogen disappear under younger sediments or the sea level and only the continent directed part of the orogen is left untouched. The Appalachians, Apennines, and the Caledonian mountains of Norway represent only sides of orogens left above sea level, the other sides having mostly sunken. For this reason there are many orogens with only one side, and that directed towards the continent.

Some oceans of the world, such as the Atlantic, Arctic, and Indian Oceans, are characterized by coasts having a definite faulted appearance. The Indian Ocean has faulted coasts in Africa and Australia. The famous East-African graben-system shows the effects of intracontinental tension on a large scale. Likewise in north-western Australia applied tensional stresses originated a

graben in the Bonaparte Gulf area. Vast outpourings of plateau-type basalts of Lower Cambrian age are known from the northern part of Western Australia to east of the Kimberley block and on it. These basalts outflowed from deep fissures of the earth's crust caused by regional stresses. Although the Bonaparte Gulf area was affected by later regional horizontal and thrust movements, partly modifying its structural configuration, it can be shown that the initial structural control in this area was graben-faulting due to regional tension. Similar basalts to the Cambrian ones of the Kimberley block can be found in the northeast part of Africa and on the Deccan Plateau. The outpouring of these last two sequences of basalts commenced at the end of the Cretaceous, but, in spite of the age difference, all three occurrences of basalts are similar from the structural point of view, all having been outpoured as a result of regional tension of the earth's crust.

The next phase in the life of the orogen is curving and breaking in pieces as a result of horizontal movements, a feature well shown in the great orogens of the world such as the Western Alps, Carpathians-Balkans, and Gibraltar. Island chains also show horizontal movements, being commonly broken in pieces and showing torsion of individual island pieces. Excellent examples of broken up orogens are the Antilles and Japan. The author has already discussed the fragmentation of the Bismarck Archipelago (16).

The median fracturing and curving of orogens, and the breaking of island chains are all due to large scale horizontal movements of geoplasma termed bathyrheal underflow. As was mentioned above, Kraus postulates two zones in the earth's crust responsible for horizontal movement: the hyporheon extending to 200 km depth and the bathyrheon extending to 800 km depth. The hyporheon building the orogen affects an area not much more than 2,000 km long (the usual length of an orogen). As the working area of the bathyrheon is located much deeper, it affects a much larger crustal area.

Kraus (*7*, p. 545) pointed out the more important indications in the earth's crust of the presence of bathyrheal underflow, viz., longitudinal stooking, horizontal movements along deep-seated faults, movements of block fields, torsion of large and small blocks. The direction of movement of the bathyrheon has remained the same through many periods of folding so that similar effects of bathyrheon movement are seen in both ancient and more recent times. Effects of bathyrheal underflow indicate a very slow but very constant regional flow extending to 800 km depth. The bathyrheon carried on its back the broken pieces of the orogen, which were of geosynclinal-hyporheal origin.

Kraus (*7*, p. 432) has stressed the importance of regional drift in the southwest Pacific area. The eastern continuation of the continent of Australia, which was of hyporheal-orogenetic origin, was broken in pieces and drifted on the bathyrheal underflow towards the east-southeast and northeast. The continent of Australia itself did not follow this movement. The author believes that the movements occurring in the northern part of the Northern Territory were caused by the bathyrheal underflow. The drag of the underflow subjected the continent of Australia to comparatively great stresses. In

early times the effect of the bathyrheal underflow on the northern part of the Northern Territory was greater than it is today because then this part of the continent was not as well consolidated as it is now. The bathyrheal underflow acted on the separate crustal blocks, which mostly consisted of granite massifs. One such block was the Cullen Granite, which was rotated in an anticlockwise direction by the bathyrheal underflow and thus gave rise to the couple that affected the area north of Katherine. To the west of the north end of the Cullen Granite are several small granitic bodies, e.g., the Brock's Creek Granite. This is a different type of intrusion from the Cullen Granite —it is of the synchronous type, while the Cullen Granite is of the subsequent type. It is assumed that these small granite bodies partly represent the crustal blocks existing to the west of the north end of the Cullen Granite. When the Cullen Granite was rotated, some of these blocks moved towards the southeast. In the case of the Prince's Springs Granite this movement caused the shearing in the anticline of the Burrundie Uranium Prospect. Farther west, the Mt. Shoobridge Granite also moved to the southeast, but the Brock's Creek Granite either did not move or moved a little to the northwest. Shearing in the anticline between the Brock's Creek and Mt. Shoobridge Granites arose from the relative movement of these two blocks. Farther to the northwest, the anticline of the George Creek Uranium Prospect was sheared in an approximately meridional direction, and this same shear zone continues to the north through the Adelaide River Uranium Prospect.

So it is clear that the present configuration of the crustal blocks of the area was determined by the northeasterly bathyrheal underflow that moved the various blocks relative to each other and also rotated the Cullen Granite block. The direction of the bathyrheal underflow is shown by the present positions of the blocks and also by the directions of their previous movements.

The author's experience of uranium deposits at Burrundie, George Creek, Brock's Creek, the western margin of the Arnhem Land Plateau and Rum Jungle indicates that the uranium mineralization is favored by sheared anticlines and northeast-trending faults where the rocks have been extensively shattered. It seems clear that in the future the search for uranium should be concentrated on such structural features. The shearing and shattering of the rock arose from the action of the bathyrheal underflow on the crustal blocks of the area.

In the present short paper the author has tried to interpret the structural phenomena encountered in the northern part of the Northern Territory and relate them to the uranium mineralization. Investigations of the structures began only recently and as yet not very much work has been done. However, it seems clear to the author that movements of crustal blocks were caused by the bathyrheal underflow, and that these movements favored uranium mineralization in the area.

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AUSTRALIA,
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URANIUM DEPOSITS OF THE NORTHERN PART OF THE BOULDER BATHOLITH, MONTANA[1]

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ABSTRACT

Uranium minerals and radioactivity anomalies occur in many silver-lead veins and chalcedony veins and vein zones in the Boulder batholith of southwestern Montana. Pitchblende has been identified in a few silver-lead veins. These silver-lead veins occupy shear zones along which there is no evidence of large-scale lateral displacement. The wall rock adjacent to the veins is intensely silicified and sericitized quartz monzonite and granodiorite. The veins have yielded substantial quantities of lead, silver, zinc, and gold. The silver-lead veins consist principally of galena, sphalerite, tetrahedrite, chalcopyrite, and pyrite in a gangue of light- to dark-gray quartz, altered rock, gouge, and subordinate chalcedony and carbonate minerals. No anomalous radioactivity nor uranium minerals have been found in similar veins in prebatholithic rocks of the area.

Chalcedony veins and vein zones, some of which are uraniferous, are distinctly different from the silver-lead veins and, with a single exception, are known only in the batholith. The chalcedony vein zones consist of one or more discontinuous stringers or veins of chalcedony and microcrystalline quartz in silicified and sericitized quartz monzonite and granodiorite, and in less strongly altered alaskite. Only small amounts of silver ore have been produced from these chalcedony veins and vein zones.

[1] Publication authorized by the Director, U. S. Geological Survey.

All of the veins are early Tertiary in age, but the silver-lead veins probably are older than the chalcedony veins. Uranium is closely associated with chalcedony and microcrystalline quartz in both types of veins. This association suggests that all of the uranium in the area is of the same age. If so, some of the silver-lead veins must have been reopened during the period of chalcedony vein formation.

INTRODUCTION

THE Boulder batholith in western Montana extends from a few miles south of Helena to about 20 miles south of Butte. The "northern part of the batholith," as used in this report (Fig. 1), includes most of the batholith north of the latitude of Boulder and a narrow strip near the east margin of the batholith south of Boulder. This area lies between the Elkhorn mountains on the east and the rather broad, high-level surface making up the Continental Divide on the west. Although the area is mountainous, the topography is not rugged but is characterized by smoothly rounded ridges commonly about 1,000 feet above the major valleys. Most of the higher valleys were occupied by glaciers in the Pleistocene epoch, but typical alpine cirques are rare.

Early in the spring of 1949 uranium minerals were discovered in veins in the batholith near Boulder, Montana. This discovery led to additional discoveries near Clancy later that summer. Subsequently, more than 100 radioactivity anomalies have been detected by prospectors and by geologists of the U. S. Atomic Energy Commission and the U. S. Geological Survey.

Detailed geologic mapping of the northern part of the batholith was begun by the U. S. Geological Survey in 1950 on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission. The study of the uranium deposits has been made an integral part of the U. S. Geological Survey's study of the geology and mineral deposits in the area south of Helena and north of Butte between the Townsend Valley about 30 miles east of Boulder and the Deer Lodge Valley about 30 miles west of Boulder.

The author is indebted to the geologists of the U. S. Geological Survey who have mapped in the area and have made their information available to him for this report, and particularly to Darrell M. Pinckney, Samuel Rosenblum, and Daniel Y. Meschter for their aid in the study of the uranium deposits. The writer also appreciates the kind cooperation of all the mine owners in the area.

GENERAL GEOLOGY

General Statement

Previous geologic work in this area has been of a reconnaissance nature in connection with studies of the mineral deposits in and near the Boulder batholith. The most complete studies are by Knopf (5) Billingsley and Grimes (2), and Pardee and Schrader (7). Only a brief summary of the geology is included here.

The principal rocks of the area are quartz monzonite and granodiorite of the Boulder batholith. These rocks, with a few notable exceptions, do not have a great range in mineralogical or chemical composition, but they have a

considerable range in texture and fabric. In the detailed mapping the batholith was divided into 23 units based principally on the textural differences apparent in hand specimens.

The rocks of the batholith cut sedimentary rocks ranging from Precambrian to Mesozoic in age near the northern margin of the batholith and volcanic rocks of Cretaceous age elsewhere. The volcanic rocks comprise fine- and coarse-grained fragmental rocks, mainly of andesitic composition, tuff flows [2] of quartz latitic composition, and subordinate lava flows. Associated with the volcanic rocks are numerous diorite porphyry intrusive bodies. The distribution of the pre-batholithic volcanic rocks suggests that only the upper part of the batholith has been uncovered within the area.

The batholithic rocks and locally the older volcanic rocks near the margin of the batholith have been intruded by silicic rocks—including aplite, alaskite, alaskite-porphyry, and pegmatite—all designated as alaskite on Figure 1. The silicic rocks occur principally as dikes, but gently dipping sheets are common and a few large bodies of irregular shape have been recognized. Gradations between two or more of the above types are common in a single outcrop. Most of the alaskite is confined to a moderately well-defined, northeastward-trending zone that approximately parallels the eastern boundary of the batholith.

The youngest consolidated rocks in the area are rhyolite and dacite. The rhyolite in the western part of the area occurs almost exclusively as flows, remnants of which now cap mountains and ridge crests, whereas most of the small rhyolite bodies shown in the northeastern part of Figure 1 are plugs or dikes. The dacite occurs as tuff beds and dikes. Almost all of the dikes are in a northeastward-trending zone somewhat better defined than the zone of alaskite intrusions (Fig. 1). The large area of dacite near the center of the map consists mainly of tuff and other fragmental rocks and is cut by many small dacite dikes. Most of the dacite tuff in the area occurs as valley-fill or as remnants on valley walls. The surfaces on which the dacite tuffs and rhyolite flows rest indicate that extensive erosion took place between the intrusion of the batholith and the extrusion of the volcanic rocks.

There is no direct evidence of the relative ages of the dacite and rhyolite because the two rocks have not been observed in contact, but geomorphic evidence suggests that the rhyolite may be older than the dacite. In the map area the rhyolite, which appears to be more resistant to erosion than the rather poorly consolidated dacite tuff, caps ridge crests and appears to have been deposited on a surface of relatively low relief. The dacite tuff appears to have accumulated in valleys at a somewhat later stage of erosion.

Structural Features

Detailed mapping in the batholith has shown many strong northeast- and east-trending structures. Several gross features of the area, such as the long dimension of the batholith, the zone of alaskite intrusions, the belt of dacite dikes, and many of the larger stream valleys, are oriented N 20° E to N 30° E.

[2] For a discussion of tuff flows see Fenner (4).

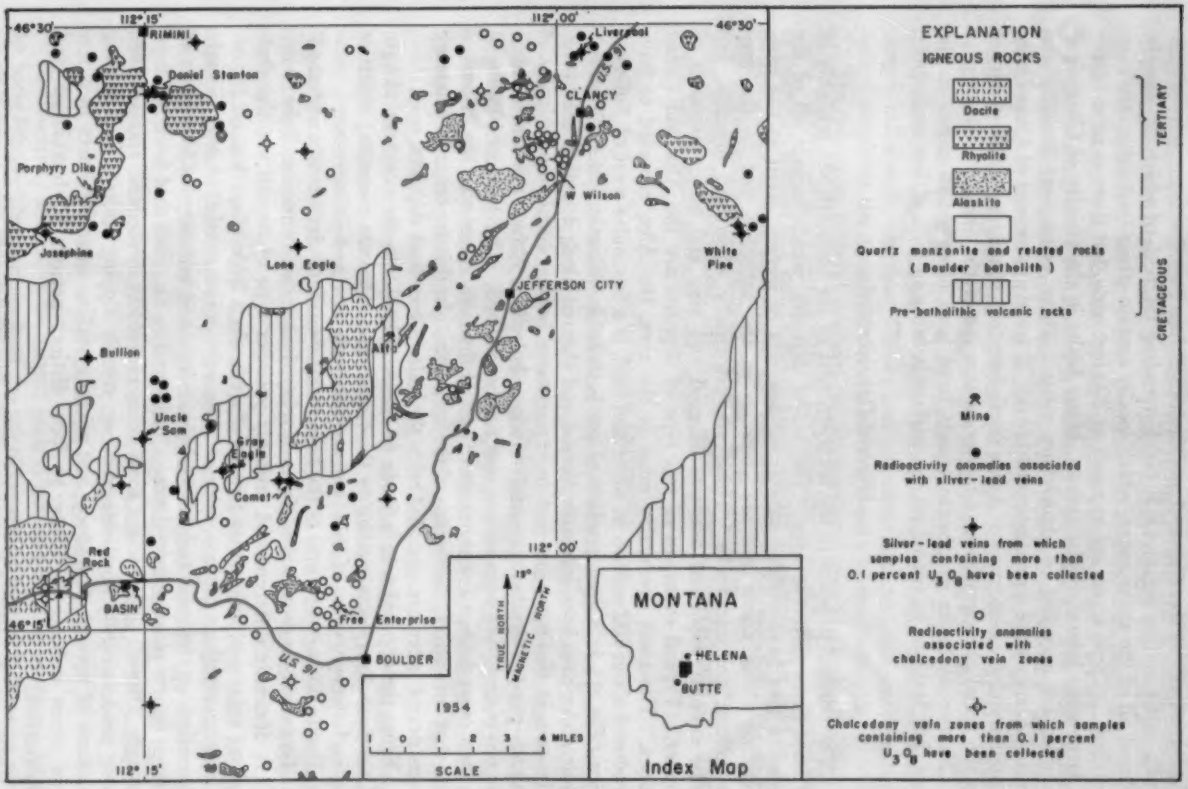

FIG. 1. Generalized geologic map of the northern part of the Boulder batholith, Montana, showing uranium deposits and radioactivity anomalies.

Numerous veins, shear zones,[8] and faults fall into two dominant sets—a generally east-trending set, and a N 60° E-trending set, both of which dip steeply. Almost all of the shear zones, which locally contain silver-lead veins, are east-trending. These zones are as much as 200 feet wide, but there is no evidence of large-scale lateral displacement. Many faults in the vicinity of Clancy and Boulder are occupied by chalcedony veins. These veins near Boulder and west of Clancy have a predominantly N 60° E trend; those east of Clancy have a predominantly east trend. A few north-trending structures can be observed on the aerial photographs and topographic maps of the area.

Numerous faults of diverse trends have been observed in mines in the area, but few can be traced on the surface because of lack of key rock units.

Mineral Deposits

The mineral deposits in the northern part of the batholith are probably of at least three different ages. The oldest deposits, which include all of the deposits that have yielded substantial amounts of metals, occur in the east-trending shear zones and are common in the batholith and in the pre-batholithic volcanic rocks. These are principally silver-lead deposits, but some contain important amounts of gold and zinc and minor amounts of copper. Typical examples of this type of deposits are the Alta and Comet mines. The most productive mine in the area, the Alta, reported to have produced about $32 million in silver and lead, is a few miles west of Jefferson City (Fig. 1) in a roof pendant of pre-batholithic volcanic rocks. The volcanic rocks have been intensely altered and sheared along a well-defined zone. The ore, in distinct veins and in replacement bodies, consists principally of galena, pyrite, tetrahedrite, and minor sphalerite. Above the water table, the ore bodies have been almost completely oxidized. Ore bodies of like type at the Comet mine, a few miles southwest of the Alta, occur on a similar structure that cuts quartz monzonite of the batholith. In this report, silver-bearing veins near Clancy are included with the older silver-lead deposits.

From the approximate latitude of Basin (Fig. 1) to the northern margin of the batholith, veins similar to the Comet and Alta are common; south of Basin, however, veins of this type are relatively few and unimportant.

Dacite dikes cut several of the base metal veins, and dacite tuffs and rhyolite flows rest on erosional surfaces developed after the formation of the veins.

A distinctly different and probably younger type of deposit are the chalcedony veins and vein zones that locally contain a little silver but no important concentrations of base metals. The vein zones consist of one or more discontinuous stringers and veins of chalcedony and microcrystalline quartz in altered quartz monzonite and granodiorite and in alaskites that have not been strongly altered. The zones have been repeatedly brecciated and silicified along predominantly northeast-trending, steeply dipping faults. Crosscutting relations of several chalcedony and microcrystalline quartz veinlets in a few vein zones indicate as many as four distinct periods of brecciation and silicification.

[8] Shear zone is used in this report in a purely descriptive sense to mean a zone of closely spaced surfaces on which one wall has moved relative to the other producing slabs or slivers of rock.

All of the chalcedony vein zones are younger than the alaskite and most of them are older than the dacite. Dacite dikes cutting the vein zones are relatively common, but in a few locations chalcedony vein zones cut dacite dikes. Crosscutting relations at one location suggest that a dacite dike was intruded during the formation of a chalcedony vein zone. The dike appears to cut the early microcrystalline quartz and later dark-gray to black chalcedony and in turn is cut by a small light-gray chalcedony veinlet that may represent the final phase of silicification in the formation of the chalcedony vein zone. These relations suggest that the formation of the chalcedony veins and vein zones took place over a considerable period of time.

The chalcedony vein zones are localized in two distinct areas of several square miles each, one near Clancy and one near Boulder, and are relatively rare throughout the remainder of the northern part of the batholith.

The youngest mineral deposits in the northern part of the batholith are small deposits of gold in rhyolite of Tertiary age near Rimini. The rhyolite is intensely altered and cut by many small quartz veinlets. The gold is disseminated throughout the rhyolite and concentrated in limonite-filled fractures. The largest mine in deposits of this type is the Porphyry Dike mine, about 5 miles southwest of Rimini, which has been operated sporadically for many years, but is inaccessible at present.

URANIUM DEPOSITS

Radioactivity anomalies have been detected at many places in the northern half of the batholith, but very few occurrences have been found elsewhere in or around the batholith. One significant exception is a small uranium deposit associated with the chalcedony vein zone a few miles west of Butte. In the Butte district only very slight radioactivity and traces of pitchblende have been detected at random throughout the extensive mine workings, although the production of other metals from the Butte district far exceeds the total production from all the other districts in the batholith.

All but two of the known radioactivity anomalies are in the rocks of the batholith. These two are in pre-batholithic volcanic rocks at the Red Rock mine, and at the Monarch mine about 9 miles southwest of Rimini. At the Monarch mine the uranium seems to be restricted to a very small area along a fault surface and its relation to the other mineral deposits in the mine is not known.[4]

Uranium minerals and anomalous radioactivity have been found in and adjacent to the silver-lead deposits, and in the chalcedony veins and vein zones. No structural nor mineralogical differences were noted between the silver-lead deposits in the batholith and those in the pre-batholithic volcanic rocks except that uranium minerals have been found only in the deposits in the batholith.

Uranium Associated with Silver-Lead Veins

Radioactivity anomalies associated with silver-lead deposits in the rocks of the batholith are common north of the approximate latitude of Basin and rare south of Basin (Fig. 1). Most of the mines are inaccessible at present, and

[4] L. D. Jarrard, oral communication, 1954.

with few exceptions the only information concerning the relations between uranium and the other metals is obtained from study of ore specimens from dumps.

Comet Mine.—The Comet mine is in the Comet-Gray Eagle shear zone in quartz monzonite near the roof of the batholith. The shear zone, which dips steeply and trends about N 80° W, has been traced for a distance of about 6 miles. Displacement along it apparently has been slight. The shear zone cuts intensely altered pre-batholithic volcanic rocks and quartz monzonite, and slightly altered alaskitic rocks; several dacite dikes cut the zone and are not sheared nor altered. Several silver-lead mines, of which the Comet is the largest, are situated along the zone. Radioactivity has been detected on the dumps of five of these mines, but geiger counter and scintillation counter traverses along the entire length of the zone failed to disclose any radioactivity anomalies along the trace of the outcrop at the surface. This may be the result of thick cover and thorough leaching of the uranium from the zone near the surface.

The total value of silver, lead, zinc, gold, and copper produced from the Comet mine is reported to have exceeded $20,000,000. The mine was last worked from 1934 to 1941; during this time the production was about $3,000,000 from ore that ranged in value from $7 to $10 per ton in combined silver, lead, zinc, gold, and copper (1).

The Comet vein has been developed to a depth of 960 feet by a vertical shaft and for a strike length of 2,200 feet by eight principal levels. None of the workings were accessible at the time the field work was done on which this report is based. No ore was mined from below the 700 level, and most of the production came from above the 500 level. Three principal veins that follow the trend of the shear zone and dip steeply to the south and several splits from these veins were explored.

Ore minerals identified in dump samples are galena, sphalerite, pyrite, tetrahedrite, chalcopyrite, and arsenopyrite. The gangue is chiefly altered wall rock and quartz; some of the quartz is a clear crystalline variety and some a dark bluish-gray, fine-grained variety. The wall rock is dominantly quartz monzonite and subordinately alaskite. Adjacent to the vein, the quartz monzonite has been strongly silicified, sericitized, and argillized.

Moderate to high radioactivity has been detected at several places on the dump, and samples containing as much as 0.52 percent uranium have been collected; but no uranium minerals have been identified from these samples. The amount of uranium in the samples is considered significant because the dump material has been exposed to weathering for at least 10 years and possibly 35 years or more, and much of the uranium may have been leached by surface waters.

Gray Eagle Mine.—The Gray Eagle mine is on the Comet-Gray Eagle shear zone about 1½ miles west of the Comet mine. Knopf (5, p. 121) and Pardee and Schrader (7, p. 287–289) described the mine. It was last operated in 1937 and was inaccessible at the time the field work was done on this report. The value of silver, lead, zinc, gold, and copper produced is estimated to be about $1,000,000. The mineralogy of the vein and wall rock is similar to that at the Comet mine.

Radioactivity at the mine, first reported by geologists of the U. S. Atomic Energy Commission on June 4, 1951, is largely confined to one part of the dump, part of which has been shipped to the East Helena smelter for the silver content. Several strongly radioactive samples have been collected from the dump. A sample of weathered vein material that contained quartz, pyrite, a sooty black mineral, and a soft yellow mineral assayed 2.2 percent uranium. The sooty mineral is probably pitchblende for an X-ray powder picture of the sooty black mineral showed a very poor, possibly cubic pattern, and after ignition an X-ray powder pattern of the same mineral matched the standard U_3O_8 pattern. Spectroscopic analysis of a sample of the yellow material showed major iron and silicon, and minor uranium, calcium, magnesium, aluminum, and manganese, and a trace of zirconium. This material unquestionably contains secondary uranium minerals, but they could not be identified specifically. A sooty black mineral intimately intermixed with pyrite was separated from gray crystalline quartz and identified as uraninite. Wright and Bieler (11, p. 22) state that uraninite has extensively replaced pyrite.

Other Silver-Lead Mines.—Selected samples that contain more than 0.1 percent U_3O_8 have been collected from the dumps of many other silver-lead mines in the batholith rocks. Among these are the Josephine, Daniel Stanton, Liverpool, Bullion, Uncle Sam, White Pine, and several unnamed properties (Fig. 1). Radioactivity has been detected on many other mine dumps.

Uranium Deposits Associated with Chalcedony Vein Zones

Many radioactivity anomalies have been detected in and adjacent to chalcedony vein zones in the batholith. Uranium ore has been produced from two mines in these zones; the Free Enterprise mine has produced a few tons of high-grade ore and about 150 tons of low-grade ore (8, p. 147), and the W Wilson mine has produced several hundred tons of moderately high-grade ore.

In the two areas where chalcedony vein zones are common—near the Free Enterprise mine and in the vicinity of Clancy—the topography is characterized by rounded hills commonly only a few hundred feet above the valley bottom. The vein zones, ranging from less than 1 foot to more than 10 feet in thickness, typically crop out conspicuously and some can be traced for more than a thousand feet.

W Wilson Mine.—The W Wilson mine is about 1½ miles southwest of Clancy. Uranium minerals were first discovered along the outcrop of the vein zone in 1949, and the geology of a few square miles in the vicinity of the mine was mapped in 1950 by Roberts and Gude (9). Subsequently, detailed studies of the mine were made by D. Y. Meschter and by Wright et al. (12). Most of the following information is summarized from the reports of these workers.

The W Wilson vein has been explored by more than 3,000 feet of drifts, crosscuts, and raises. Uranium ore has been mined from two ore bodies along the main vein and from one small ore body along a smaller vein parallel to the main vein.

The dominant rock type in the vicinity of the mine is quartz monzonite

with an approximate composition of 45 percent plagioclase (An 30–35), 25 percent potassic feldspar, 20 percent quartz, 7 percent biotite, and 3 percent hornblende. The quartz monzonite is cut by a few thin dikes of alaskite.

Adjacent to each chalcedony vein, the quartz monzonite is typically altered in poorly defined gradational zones of decreasing intensity outward from the vein. The innermost zone immediately adjacent to the vein is characterized by silification; seritization characterized an intermediate zone and beyond that lies a zone of kaolinization. This alteration is similar to that accompanying the silver-lead veins and non-uraniferous chalcedony veins, and no particular feature of the alteration was recognized as specifically diagnostic of or peculiar to the uranium mineralization.

The W Wilson vein zone consists of from 1 to 5 veins of chalcedony and microcrystalline quartz, locally as much as 3 feet thick but averaging only a few inches. The interlacing of individual veinlets of quartz and chalcedony along the strike and dip of the vein has resulted in a pattern that resembles crude netting. The chalcedony in the vein zone is characteristically dark-gray to black, but locally chalcedony of lighter shades of gray is present. At least three, and possibly four, generations of silica and at least three periods of brecciation during formation of the vein zone are indicated.

Uranium minerals were first discovered at the W Wilson mine in two ore bodies that contained sparse nodules and veinlets of pitchblende and relatively abundant yellow and orange secondary uranium minerals; uranophane, phosphuranylite, uranocircite, meta-autunite, and a mixture of oxides referred to as gummite. A few secondary minerals, mainly metatorbernite, meta-autunite, and uranophane, are sparsely distributed along and adjacent to fractures outside of the ore bodies indicating the transportation and redeposition of some of the uranium by meteoric water.

The two very irregular, lenslike ore bodies ranged from less than 1 foot to 5 feet in thickness and were as much as 50 feet in length. The ore bodies plunged steeply to the northeast and were separated laterally by about 10 feet of altered quartz monzonite. One extended to a depth of about 30 feet and the other to a depth of about 70 feet.

Meschter [5] stated that at least three periods of silicification in the W. Wilson mine can be recognized. The first period consists of clear microcrystalline quartz, the second of black and dark-gray chalcedony, and the third of clear microcrystalline quartz. He concluded that pyrite, chalcopyrite, and pitchblende are essentially contemporaneous with the dark gray to black chalcedony.

Wright et al. (12, p. 5) state: "Autoradiographs have shown that the most recent of the several varieties of vein chalcedony is usually the most radioactive; this material is generally found in veinlets and in the cementing material enclosing breccia fragments. Almost all of the late, radioactive silica is dark gray or black. Semiquantitative spectroscopic analyses and radiometric counts of carefully micropicked fractions of the various chalcedony color varieties have shown a tendency for Ag, As, Co, Cu, Mn, Mo, Ni, Pb, and Sn to be concentrated in the dark gray and black colors, along with uranium. Co-

[5] D. Y. Meschter, personal communication, 1953.

balt, nickel, silver, and copper, common associates of uranium in vein deposits, generally vary with uranium."

Because galena and sphalerite have been found only in trace amounts in the W Wilson vein the relations between these minerals and the uranium minerals are not known.

Red Rock Mine.—One of the two known occurrences of uranium minerals in the pre-batholithic volcanic rocks is at the Red Rock mine about 1½ miles west of Basin. The batholith is exposed about 3,000 feet northeast of the mine but may underlie the volcanic rocks at the mine at a relatively shallow depth.

The Red Rock vein consists of light-gray chalcedony in intensely silicified, sericitized, and brecciated volcanic rocks. The entire altered zone is about 300 feet wide and forms a conspicuous northeasterly trending ridge for several thousand feet on each side of U. S. Highway 91. A conspicuous outcrop along this zone on the north side of the highway is locally called Indian Head Rock. The Red Rock vein differs from the typical chalcedony vein zone of the batholith in that it is a single vein of chalcedony with gradational margins rather than a series of anastomosing veinlets with sharp boundaries.

The vein ranges from less than 1 foot to about 4 feet in thickness. It is exposed in two adits—one north of the highway and one south of the highway —along a well-defined fault surface that shows evidence of post-mineralization movement. The wall rock adjacent to the vein has been almost entirely replaced by chalcedony and fine-grained, disseminated pyrite. Within the vein, sharply angular fragments of the altered wall rock are cemented by a reddish-gray chalcedony that contains no pyrite. The final phase of silicification is represented by microcrystalline quartz in small veinlets and lining vugs.

Although no primary uranium minerals have been identified from the Red Rock vein, finely disseminated pitchblende is probably present in the reddish-gray chalcedony. Locally, meta-autunite has been deposited in fractures in the vein and adjacent wall rock from circulating meteoric water.

Uranium Associated with Veins of Mixed Type

Uranium minerals and radioactivity anomalies have been found in and adjacent to a few veins that have some characteristics of both the silver-lead veins and the chalcedony veins and veinzones. They contain abundant amounts of lead and silver minerals and small amounts of sphalerite in a gangue that is predominantly microcrystalline quartz and chalcedony. The mineral assemblage of these veins suggest that they were formed either during an intermediate period of mineralization or during both of the periods described above. The vein in the Lone Eagle mine is an example of a vein of mixed type.

Lone Eagle Mine.—The Lone Eagle mine is on the South Fork of Quartz Creek about 9 miles southwest of Clancy (Fig. 1). The area, although mountainous, is of moderate relief, and altitudes range from 5,000 to 7,500 feet. The vein crops out at only one point, and because the hill above the mine is covered by a thick mantle of soil and a heavy growth of conifers, it cannot be traced on the surface.

The vein is in intensely altered quartz monzonite in which biotite is altered to chlorite and the feldspars are altered to a light-gray to greenish-gray mixture of clay and sericite. Silicified zones of quartz monzonite adjacent to the quartz veins and veinlets range in thickness from less than an inch adjacent to the small quartz veinlets to several feet adjacent to the large radioactive vein about 110 feet from the mine portal (Fig. 2). Faulting and shearing are common throughout most of the mine.

The radioactive vein strikes about N 45° E, dips from about 50° to 75° SE, and ranges from 1 to 5 feet in thickness. It is cut by several east-

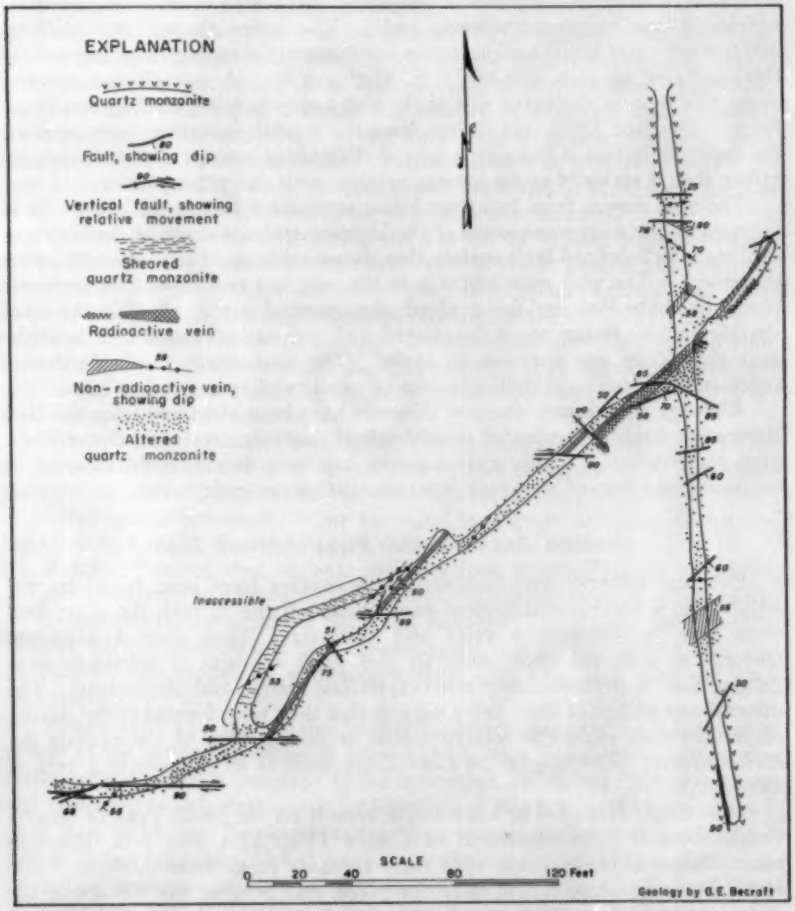

FIG. 2. Geologic map of the Lone Eagle mine, Jefferson County, Montana.

trending, steeply dipping faults, and in each case the vein on the south side of the fault is offset to the west.

The Lone Eagle vein consists principally of light gray to black microcrystalline quartz and chalcedony. Pyrite is common in the vein and in the altered wall rock adjacent to the vein. Veinlets of fine-grained pyrite cutting pyrite cubes indicate that at least two generations of pyrite are present in the vein. Sphalerite and galena are present locally along the vein. Uranium is present in two forms: as small irregular blebs of pitchblende in the vein and as a sooty black material coating irregular fractures in the vein and in the altered wall rock adjacent to the vein.

Wright et al. (12, p. 67) state that pitchblende has extensively replaced pyrite and in some places has replaced chalcedony and sphalerite that filled fractures in pyrite. They also observed a second generation of sphalerite and pyrite in veinlets cutting the pitchblende and conclude that the paragenetic ". . . sequence appears to have been as follows:

(1) Microcrystalline quartz which continued throughout the deposition.
(2) Well-formed pyrite.
(3) Sphalerite with chalcopyrite, galena, and finely crystallized pyrite.
(4) Pitchblende and cryptocrystalline chalcedony with minor pyrite.
(5) Sphalerite and galena with cryptocrystalline chalcedony and minor pyrite.
(6) Argentite (?)."

Age of the Uranium Deposits

All of the known uranium deposits are post-alaskite and pre-dacite. Data obtained by measuring the lead-alpha activity ratio in zircon suggest an age of about 60,000,000 years for the alaskite (3)—late Late Cretaceous or Paleocene. Weed (10) reports that dacite tuffs at the south end of the Deer Lodge Valley are contemporaneous with lake beds of Miocene age, but in the Townsend Valley quartz-bearing tuffs in a similar setting are early Oligocene in age (6, p. 27). These two observations indicate that the dacite may be either Miocene or Oligocene in age.

In the chalcedony vein zones the uranium was deposited with the dark gray to black chalcedony, which was deposited late in the formation of the vein zones but prior to the intrusion of the dacite. In the silver-lead veins also, the uranium appears to be intimately associated with dark gray to black chalcedony or microcrystalline quartz. In several of the silver-lead veins, the chalcedony cuts quartz veins containing galena and sphalerite and therefore is interpreted to be later than the sulfide mineralization. In the Lone Eagle mine, Wright et al. (12, p. 67) state that sphalerite and pyrite were observed in veins cutting the pitchblende.

The intimate association of uranium with dark-gray to black chalcedony or microcrystalline quartz in the chalcedony vein zones and in the silver-lead deposits suggests that most of the uranium mineralization may be of the same age and that many of the silver-lead veins were reopened during the period of uranium mineralization.

Age determination using a uranium-lead method has not been possible because pitchblende collected from the chalcedony vein zones is intimately mixed with secondary minerals and a sample clean enough for age determination has not been obtained. The pitchblende associated with the silver-lead deposits has not been found in sufficient amounts for age determination.

SUMMARY AND CONCLUSIONS

Uranium minerals and radioactivity anomalies are common in chalcedony veins and vein zones and in silver-lead veins in the northern part of the Boulder batholith. Only two anomalies have been detected in the pre-batholithic volcanic rocks although the structure and mineralogy, uranium minerals excepted, of the silver-lead veins appear to be similar in the batholith and the pre-batholith rocks.

Because of the intimate relation between the uranium minerals and dark gray to black chalcedony and microcrystalline quartz, all of the uranium deposits are thought to be closely related in origin and age. The uranium is believed to have been deposited from hydrothermal solutions in early Tertiary time, but its exact age is not known.

Known deposits in chalcedony veins and vein zones are small though a few are moderately high grade. The chance of finding large tonnages of ore in veins of this type is considered slight. Because of the large size and continuity of the structures along which the silver-lead veins have been formed, large minable uranium ore bodies may occur in some of these veins.

U. S. GEOLOGICAL SURVEY,
SPOKANE, WASH.,
Feb. 24, 1956

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THE STABILITY OF SMITHSONITE[1]

R. I. HARKER AND J. J. HUTTA

ABSTRACT

The P_{CO_2}-T curve for the reaction $ZnCO_3 \rightleftharpoons ZnO + CO_2$ has been determined experimentally up to 50,000 lbs/in.^{2} of CO_2. At 10,000, 30,000 and 50,000 lbs/in.^{2} the curve passes through 310, 410 and 460°C respectively.

INTRODUCTION

THE importance of zinc is evident from the fact that it ranks fourth in tonnage of metals produced in the U.S.A. The most important and widespread zinc ores are sphalerite (ZnS), smithsonite ($ZnCO_3$), hemimorphite ($(ZnOH)_2SiO_3$) and willemite (Zn_2SiO_4), and these four minerals may be associated with one another.

This paper describes the work carried out in order to determine the limits of stability of smithsonite and zincite, according to the equation $ZnCO_3 \rightleftharpoons ZnO + CO_2$, under varying pressures of CO_2 between 5,000 and 60,000 lbs/in.^{2}. Previous attempts to determine the variation in the temperature of dissociation of $ZnCO_3$ were made by Mehmet and Valensi (1) between 0 and 770 mm Hg, but at these low pressures it was not possible to obtain equilibrium.

EXPERIMENTATION AND RESULTS

All the experimental work was carried out in cold seal pressure vessels designed by Tuttle (2). The CO_2 was supplied to these vessels by way of a hydraulic jack pump and the pressure vessels were heated by means of movable furnaces with nichrome windings. The apparatus as a whole has been described previously (3). The pressures were controlled to ± 3 percent and the temperatures to $\pm 5°$ C.

In order to establish that the P_{CO_2}-T curve for the dissociation of $ZnCO_3$ is in fact the thermal equilibrium curve, it was necessary to make the reaction go both ways. Thus, in each of the experimental runs the starting materials consisted of both $ZnCO_3$ and ZnO (+ CO_2). The materials which were used are listed below:

1) Basic Zinc Carbonate (Baker's analytical reagent),
2) Natural Smithsonite from Kelly, New Mexico,
3) Neutral Zinc Carbonate,
4) Zinc Oxide (Baker's analytic reagent),
5) Zinc Oxide prepared by heating 1) above.

[1] Contribution No. 55-47 from the College of Mineral Industries, The Pennsylvania State University.

The CO_2 which was used was the Bone Dry grade of the Matheson Company, Inc., New Jersey (99.8% pure).

The natural smithsonite from Kelly was found to be less reactive than the other starting materials and, as its exact composition was not known,

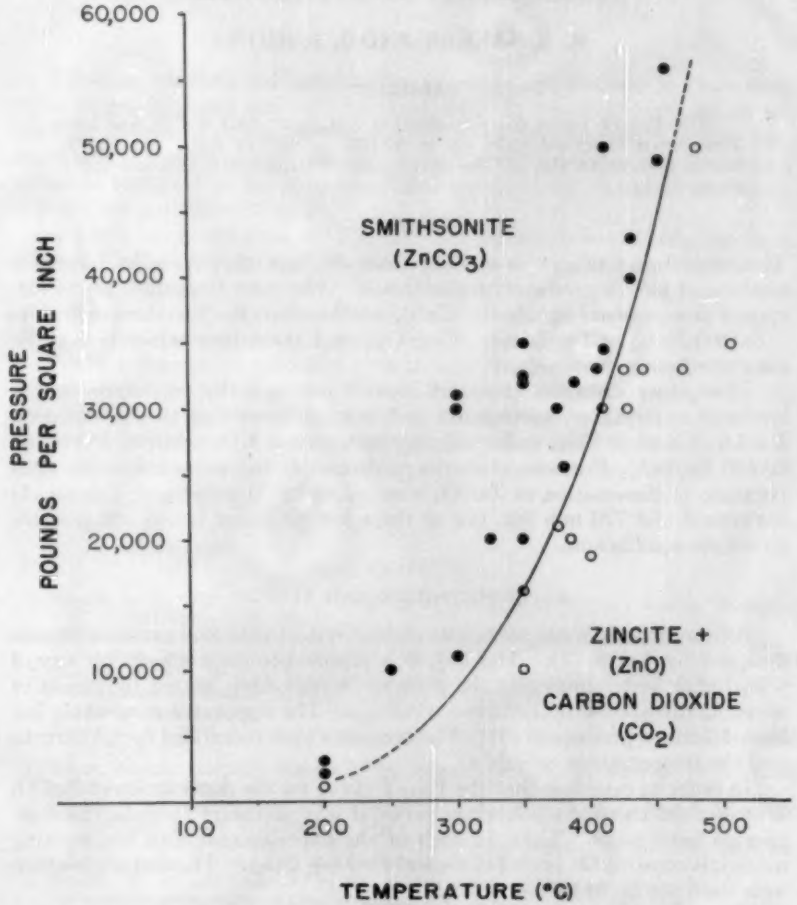

FIG. 1. Univariant pressure (CO_2)-temperature curve for the reaction: $ZnCO_3 \rightleftharpoons ZnO + CO_2$; $ZnCO_3$ stable = ●; $ZnO + CO_2$ stable = o.

it was soon discarded as unsuitable. The neutral zinc carbonate was made by placing an intimate mixture of zinc sulphate and sodium bicarbonate in a Morey bomb containing solid carbon dioxide. The bomb was then sealed and heated at 160° C for two days. After this treatment the product was

thoroughly washed, leaving very fine grained neutral zinc carbonate which was then dried and ready for use.

The starting materials were wrapped in gold foil and placed in the pressure vessel. On the high temperature side of the curve, the ZnO was stable and the $ZnCO_3$ decomposed. On the low temperature side, $ZnCO_3$ was stable and the ZnO combined with CO_2 to form carbonate. It was not necessary for the reaction to go to completion and the runs had to be made only for a sufficient length of time to show in which direction the reaction was going. For example, if at the end of a run it was found that $ZnCO_3$ had recrystallized but that ZnO showed small rims of $ZnCO_3$ then the P-T conditions of the run lay on the low-temperature side of the P-T curve. Likewise, only a small amount of $ZnCO_3$ had to decompose to indicate that a run was made on the high-temperature side of the curve. The products were identified with the aid of the X-ray spectrometer and the petrographic microscope.

The successful runs made to determine the P_{CO_2}-T curve for the reaction $ZnCO_3 \rightleftharpoons ZnO + CO_2$ are listed in Table 1 from which the curve in Figure 1 has been drawn. It was found that reaction was aided considerably when the starting materials were moistened with a little water to act as a flux. This procedure has been adopted with much success in similar experiments, e.g. during the study of the reaction $CaCO_3 + SiO_2 \rightleftharpoons CaSiO_3 + CO_2$(4). In Table 1, the runs in which the samples were dry are labeled 'd' and the ones in which they were moistened are labeled 'w'. Experiments 20 and 25, run on the low-temperature side of the curve under the same conditions of pressure and temperature and for approximately the same length of time, illustrate the effectiveness of having a little water present. In the former, the conversion of ZnO to $ZnCO_3$ is almost complete whereas in the latter, in which dry samples were used, only a very small trace of $ZnCO_3$ developed from one of the oxides.

In the majority of the runs the basic zinc carbonate was found to be the most sensitive starting material. In run 15 for example (a relatively short run at only moderate pressure and fairly close to the P-T curve) it was the only starting material to react. On heating, the water from the hydroxide component was readily given off leaving $ZnCO_3$ + ZnO (see run 18). Runs on the high-temperature side of the curve were indicated by an increase of ZnO at the expense of $ZnCO_3$, over and above that derived from $Zn(OH)_2$, while on the low temperature side of the curve, $ZnCO_3$ increased at the expense of the ZnO derived from the $Zn(OH)_2$. The relative amounts of $ZnCO_3$ and ZnO were estimated by a comparison of the intensities of the {211} $ZnCO_3$ peak and the $\{10\bar{1}1\}$ $\{10\bar{1}0\}$ and {0002} ZnO peaks of the X-ray powder diffraction patterns.

Of the two oxides which were used, one was frequently more reactive than the other, but as it was not possible to predict which would be the more reactive in a proposed run, both were usually put in together.

The products of runs 21 and 46 have been taken to indicate that the P-T conditions of these runs lie on the univariant curve because in them

TABLE 1

Run No.	Initial materials	Pressure $\times 10^{-3}$ lbs/in.^{2}	Temperature °C	Time hrs.	Products
54	*ZnO* w	56	456	21	$ZnCO_3$ + ZnO
	Basic Zn Carb. w	56	456	21	$ZnCO_3$
	$ZnCO_3$ w	56	456	21	$ZnCO_3$
	ZnO c.p. w	56	456	21	ZnO
36	*ZnO* w	50	410	18	$ZnCO_3$
	Basic Zn Carb. w	50	410	18	$ZnCO_3$
	$ZnCO_3$ w	50	410	18	$ZnCO_3$
	ZnO c.p. w	50	410	18	$ZnCO_3$
55	*ZnO* d	50	480	24	ZnO
	Basic Zn Carb. d	50	480	24	ZnO
	$ZnCO_3$ d	50	480	24	ZnO
	ZnO c.p. d	50	480	24	ZnO
53	*ZnO* w	49	450	38	$ZnCO_3$ + ZnO
	Basic Zn Carb. w	49	450	38	$ZnCO_3$ + ZnO
	$ZnCO_3$ w	49	450	38	$ZnCO_3$
	ZnO c.p. w	49	450	38	$ZnCO_3$
38	*ZnO* d	40	430	85	ZnO + $ZnCO_3$
	Basic Zn Carb. d	40	430	85	$ZnCO_3$
	$ZnCO_3$ d	40	430	85	$ZnCO_3$
	ZnO c.p. d	40	430	85	ZnO
16	*ZnO* w	35	350	32	$ZnCO_3$ + ZnO
	ZnO c.p. w	35	350	32	$ZnCO_3$ + ZnO
8	$ZnCO_3$ d	35	505	21	ZnO
	ZnO c.p. d	35	505	21	ZnO
41	*ZnO* d	34.5	410	516	$ZnCO_3$
	Basic Zn Carb. d	34.5	410	516	$ZnCO_3$ (+ ZnO)
	ZnO c.p. d	34.5	410	516	ZnO + $ZnCO_3$
18	Basic Zn Carb. d	33	390	0.25	$ZnCO_3$ + ZnO
7	Basic Zn Carb. d	33	405	61	$ZnCO_3$ (+ ZnO)
13	Basic Zn Carb. d	33	425	43	ZnO
	$ZnCO_3$ d	33	425	43	ZnO
	ZnO c.p. d	33	425	43	ZnO
10	Basic Zn Carb. d	33	440	16	ZnO
	$ZnCO_3$ d	33	440	16	ZnO
	ZnO c.p. d	33	440	16	ZnO
9	Basic Zn Carb. d	33	470	16	ZnO
	$ZnCO_3$ d	33	470	16	ZnO
	ZnO c.p. d	33	470	16	ZnO
16	Basic Zn Carb. w	32.3	350	32	$ZnCO_3$ (+ ZnO)
	$ZnCO_3$ w	32.3	350	32	$ZnCO_3$ (+ ZnO)
5	Basic Zn Carb. d	32	350	22.5	$ZnCO_3$ (+ ZnO)
6	Basic Zn Carb. d	32	390	17.5	$ZnCO_3$ (+ ZnO)
3	Basic Zn Carb. d	31	300	16	$ZnCO_3$ (+ ZnO)
4	Basic Zn Carb. d	30	300	29	$ZnCO_3$ (+ ZnO)
25	*ZnO* d	30	375	26	ZnO (+ $ZnCO_3$)
	ZnO c.p. d	30	375	26	ZnO
20	*ZnO* w	30	375	25	$ZnCO_3$ (+ ZnO)
	Basic Zn Carb. w	30	375	25	$ZnCO_3$
	$ZnCO_3$ w	30	375	25	$ZnCO_3$
	ZnO c.p. w	30	375	25	$ZnCO_3$

ZnO c.p. = Zinc Oxide (Baker's analytical reagent).
Basic Zn Carb. = Basic Zinc Carbonate ($mZnCO_3.nZn(OH)_2$, Baker's analytical reagent).
ZnO = Zinc Oxide prepared by heating the Basic Zinc Carbonate at atmospheric pressure.
$ZnCO_3$ = Zinc Carbonate prepared from Zinc Sulfate and Sodium Bicarbonate under a pressure of CO_2.
(+ $ZnCO_3$) or (+ ZnO) = Zinc Carbonate or Zinc Oxide occurring in very small amounts in the products.

TABLE 1—*Continued*

Run No.	Initial materials		Pressure $\times 10^{-6}$ lbs/in.^{2}	Temperature °C	Time hrs.	Products
21	*ZnO*	w	30	410	28	ZnO (+ $ZnCO_3$)
	Basic Zn Carb.	w	30	410	28	ZnO + $ZnCO_3$
	$ZnCO_3$	w	30	410	28	ZnO
	ZnO c.p.	w	30	410	28	$ZnCO_3$ + ZnO
23	*ZnO*	d	30	427	25	ZnO
	Basic Zn Carb.	d	30	427	25	ZnO
	$ZnCO_3$	d	30	427	25	ZnO
	ZnO c.p.	d	30	427	25	ZnO
43	*ZnO*	d	23.5	380	128	ZnO (+ $ZnCO_3$)
	Basic Zn Carb.	d	23.5	380	128	$ZnCO_3$ (+ ZnO)
	$ZnCO_3$	d	23.5	380	128	$ZnCO_3$
	ZnO c.p.	d	23.5	380	128	ZnO
15	*ZnO*	d	21	375	26.5	ZnO
	Basic Zn Carb.	d	21	375	26.5	ZnO
	$ZnCO_3$	d	21	375	26.5	$ZnCO_3$
	ZnO c.p.	d	21	375	26.5	ZnO
19	*ZnO*	w	20	325	17	$ZnCO_3$ (+ ZnO)
	Basic Zn Carb.	w	20	325	17	$ZnCO_3$
	$ZnCO_3$	w	20	325	17	$ZnCO_3$
	ZnO c.p.	w	20	325	17	$ZnCO_3$ + ZnO
24	*ZnO*	w	20	350	25	$ZnCO_3$ + ZnO
	Basic Zn Carb.	w	20	350	25	$ZnCO_3$ + ZnO
	$ZnCO_3$	w	20	350	25	$ZnCO_3$
	ZnO c.p.	w	20	350	25	$ZnCO_3$
52	*ZnO*	d	20	385	78	ZnO
	Basic Zn Carb.	d	20	385	78	ZnO
	$ZnCO_3$	d	20	385	78	ZnO
	ZnO c.p.	d	20	385	78	ZnO
2	Basic Zn Carb.	d	18.7	400	17	ZnO
	ZnO c.p.	d	18.7	400	17	ZnO
46	*ZnO*	d	16	350	105.5	ZnO + $ZnCO_3$
	Basic Zn Carb.	d	16	350	105.5	ZnO + $ZnCO_3$
	$ZnCO_3$	d	16	350	105.5	$ZnCO_3$
	ZnO c.p.	d	16	350	105.5	ZnO
17	*ZnO*	w	11	300	59.5	ZnO
	Basic Zn Carb.	w	11	300	59.5	ZnO
	$ZnCO_3$	w	11	300	59.5	$ZnCO_3$
	ZnO c.p.	w	11	300	59.5	ZnO
26	*ZnO*	w	11	300	131	ZnO + $ZnCO_3$
	Basic Zn Carb.	w	11	300	131	$ZnCO_3$
	$ZnCO_3$	w	11	300	131	$ZnCO_3$
	ZnO c.p.	w	11	300	131	$ZnCO_3$
22	*ZnO*	w	10	250	168	$ZnCO_3$
	Basic Zn Carb.	w	10	250	168	$ZnCO_3$
	$ZnCO_3$	w	10	250	168	$ZnCO_3$
	ZnO c.p.	w	10	250	168	$ZnCO_3$
11	*ZnO*	w	10	350	94	ZnO
	Basic Zn Carb.	w	10	350	94	ZnO (+ $ZnCO_3$)
	$ZnCO_3$	w	10	350	94	ZnO
	ZnO c.p.	w	10	350	94	ZnO
45	*ZnO*	d	3	200	640	ZnO + $ZnCO_3$
	ZnO	d	2	200	337	ZnO (+ $ZnCO_3$)
	ZnO	d	1	200	1222	ZnO

there has been no detectable growth either of carbonate or of oxide from the basic zinc carbonate. The other products of run 21 provide rather conflicting evidence: the oxides have formed carbonate and the zinc carbonate has formed oxide. These results are probably due to small tempera-

ture changes and gradients which are effective in causing phase changes in runs so close to the P-T curve.

The formation of ZnO from $ZnCO_3$ in run 16 and from the basic zinc carbonate in run 17 is not easy to explain but may be due to the P-T conditions momentarily entering the field of zincite + carbon dioxide during the initial heating. Once zincite has crystallized it would probably be sufficiently coarse grained, especially if moisture were present initially, to make it difficult for it to revert to carbonate. A comparison of runs 17 and 26 show that, even with a little moisture present, long runs are necessary to determine which phases are stable at low pressures and temperatures when these are close to the P-T curve.

As is usually the case with P-T curves of this nature, it is possible to draw a variety of different curves between the experimentally determined critical points. In the present study it is considered that the most accurate part of the curve is that which lies between 15,000 and 35,000 lbs/in.^{2}. From the slope of the curve at 20,000 lbs/in.^{2} and 368° C and from Kennedy's tables for the P-V-T relations in CO_2 (5) it is estimated that the approximate value for the enthalpy of the reaction under these P-T conditions is 10.8 kcals/mole.

DISCUSSION OF RESULTS

The P-T curve for the dissociation of smithsonite lies at lower temperatures than any other P_{CO_2}-T curve determined at such elevated pressures. Between 10,000 and 40,000 lbs/in.^{2} it lies approximately 400° C below the corresponding P-T curve for the dissociation of magnesite (3) and approximately 350° C below the curve for the reaction: calcite + quartz $\rightleftharpoons$ wollastonite + carbon dioxide (4).

It is perhaps surprising that zincite is not a more common mineral in view of the low temperatures of dissociation of smithsonite. It is to be expected that even under high pressures of CO_2 a low grade of metamorphism would be sufficient to drive off the CO_2 from the smithsonite. In the presence of sufficient silica, however, willemite would be expected to form instead of zincite, or, with sufficient water pressure, hemimorphite would be produced.

A low temperature of formation has always been suggested for smithsonite on the basis of its paragenesis. It is commonly associated with other low temperature minerals, such as hemimorphite, goethite, limonite, siderite and cerussite, and it is frequently said to have developed by the alteration of sulfides by meteoric waters, e.g., $ZnS + H_2CO_3 \rightleftharpoons ZnCO_3 + H_2S$. It is possible that smithsonite and zincite could be formed in a variety of ways in the earth's crust: by primary crystallization, hydrothermal alteration or metamorphism. However, no matter what reactions are involved, provided the phases are pure and crystallized in equilibrium, the presence of smithsonite or zincite indicates on which side of the P-T curve the conditions of formation lay.

ACKNOWLEDGMENT

This work was suggested by Dr. O. F. Tuttle without whose supervision and assistance it could not have been carried out.

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Editorial

THE FIFTIETH ANNIVERSARY VOLUME 1905–1955

The Fiftieth Anniversary Volume of ECONOMIC GEOLOGY, consisting of critical review articles, has recently come off the press. The Editor and contributors take pardonable pride in the fact that sales reflect a gratifying interest on the part of our profession. By the time this editorial appears, a widespread acquaintance with the volume may be assumed. For the benefit of those who have not yet seen it, the table of contents is carried on an advertising page in the back of this issue.

Our purpose, however, is not to further advertise the Anniversary Volume, but to assure our readers that the pages of the discussion section of this Journal are open to comments, criticism, discussion, and reviews of individual articles of the Volume. We hope that any of our readers interested in special subjects of the Volume will take full advantage of this invitation to submit discussions, particularly since, for a publication of this kind, comprehensive reviews of the Volume as a whole can never be completely satisfactory.

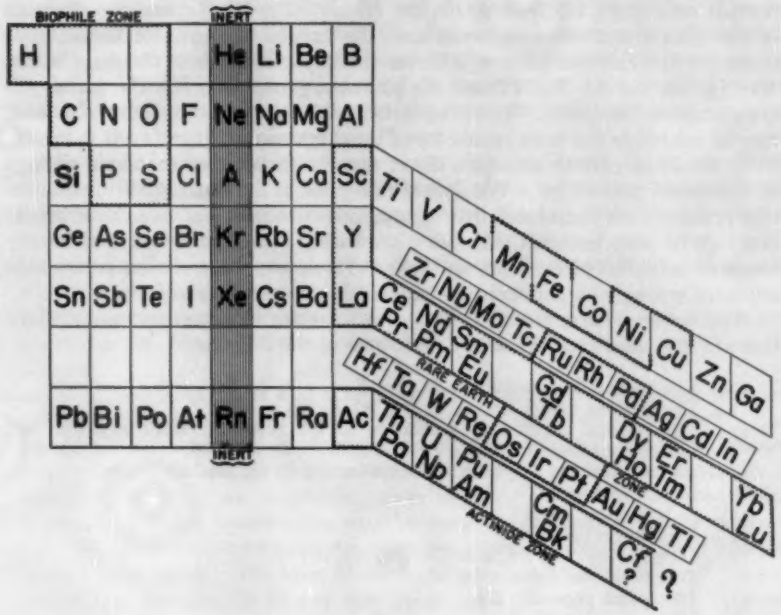
THE EDITOR

SCIENTIFIC COMMUNICATION

PERIODICITY IN ECONOMIC GEOLOGY

It is the writer's firm belief based on the observations recorded in this short note that a close relationship must exist between physical chemistry and economic geology.

It is a well accepted principle that the large part of metalliferous ore bodies evidence some form of dependence, direct or indirect, on igneous ac-


BIOPHILE ZONE
INERT
H
He Li Be B
C N O F Ne Na Mg Al
Si P S Cl A K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga
Ge As Se Br Kr Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In
Sn Sb Te I Xe Cs Ba La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Hf Ta W Re Os Ir Pt Au Hg Tl
Pb Bi Po At Rn Fr Ra Ac Th Pa U Np Pu Am Cm Bk Cf ? ?
RARE EARTH ZONE
ACTINIDE ZONE
INERT

tivity. The magma chamber is usually referred to as the ultimate source of such ore deposits. What is known of magmas is limited to the knowledge of petrology, but it appears from this viewpoint that a great deal of concentration is necessary before an economic mineral deposit results. It is reasonable to assume that the operative processes of natural beneficiation are physical-chemical in nature and subject to natural law. It also appears that a study of economic geology is a sort of random sampling of those processes.

The accompanying diagram is an arrangement of the 98 elements based primarily on the sequence of the median mass number for each of the natural elements. This is also, interestingly enough, the atomic number (proton) sequence. The non-natural elements are interpolated on the basis of their proton numbers. There is little difference, other than in arrangement, between this and any usual chemical periodic chart. In the design pattern *silicon* was used as a cornerstone; the geological importance of that element could not be ignored. The periodic arrangement is based on the fact that *germanium* is midway between *silicon* and *tin* in all respects and that *zirconium* and *hafnium* are similar in most respects. The diagrammatic basis for the periods is, therefore, physical-chemical.

In the quantitative sampling view of economic geology certain mineral and element association patterns emerge, which can also be related to the spacial or symmetry arrangement of the diagram and so appear to have some foundation in physical-chemical periodicity. For example: the economically important ores of *Ti, V, Cr, Mn, Fe, Zr, Nb, Hf, Ta, W, Re,* and the elements of the *scandium-lanthanum* series and the natural elements of the *actinide* series are associates of *oxygen,* whereas the important ores of *Co, Ni, Cu, Zn, Ga, Ag, Cd, In, Au, Hg, Tl,* and the platinum group, *Ru, Rh, Pd, Os, Ir, Pt* are associates of sulphur. This association, with the exception of *molybdenum,* may be related to the basic symmetry of the diagram.

It would be rash to attempt a direct correlation between economic geology and chemical periodicity. We should recognize at the outset that mineralization processes are plural and that the operative chemistry of natural beneficiation can be very complex, involving the mass, volume, valence, and energy levels or activities of elements and ions. However, a correlation potential is indicated strongly by parallelisms that are too numerous to be fortuitous.

The writer wishes to call attention to these further economic associations that are also spacial or symmetry associates in the diagram:

(a). The pegmatite association: *Li, Be, B*
(b). The igneous association: *Na, Mg, Al, K, Ca*
(c). The residual magmatic association of the relatively large negative and monovalent ions: *O, S, Se, Te, F, Cl, Br, I, K, Rb, Cs*
(d). The titaniferous magnetite association: *Ti, V, Cr, Mn, Fe*
(e). Manganese ore: *Mn, Fe*
(f). Cobalt ores: *Co, Ni*
(g). Nickel ores: *Ni, Cu*
(h). Copper ores: *Cu, Zn;* also *Cu, Zn, Ag, Au*
(i). Zinc ores: *Zn, Cd, Ga, In*
(j). Zirconium ores: *Zr, Hf*
(k). Niobium ores: *Nb, Ta*
(l). Barium ores: *Ca, Sr, Ba*
(m). Rubidium and caesium ores: *K, Rb, Cs*
(n). Rare earth ores: *Sc, Y,* and *the rare earth elements*
(o). Allanite ore: *U, Th;* pegmatites: *U, W;* carnotite: *U, V*
(p). Cerium ores: *Ce, Th, Nd, U*
(q). Biogenic fuels: *H, C, N, P, O, S*
(r). Aqueous deposits: *H* (OH), *C* (CO_3), *N* (NO_3), *P* (PO_4), *S* (SO_4), *F, Cl, Br, I*
(s). Bismuth ores: *Bi, Po*

(t). *As, Sb, (S)*
(u). *As, Se, Te, (S)*
(v). *Ru, Rh, Pd, Os, Ir, Pt*
(w). *Re, W, Mo;* also, *Re, Os*
(x). The rare earth and actinide association with pegmatophile elements

There are on the other hand many outstanding examples of important economic associations that seem to violate the symmetry of the diagram. For example:

(a). *Pb* with *Cu, Ag, Zn*
(b). *Mo* with *Cu*
(c). *Ga* with *Al* (an oxyphile association)
(d). *Ge* with *Zn* (a sulphophile association)
(e). *Hg* (uniquely lacking in economic associates)

These exceptions really increase confidence in the principle of basic periodicity, because *Pb, Bi, Sb,* and *As* are strongly sulphophile in economic geology, whereas *Sn, Ge, Si, C, N,* and *P* are strongly oxyphile. The association of *Pb, Bi, Sb,* and *As* with *Cu, Zn, Ag,* and *Au* may be a metallurgical association and could be attributed to the sulphophile character of the elements. Lead sulphide would tend to concentrate in a natural copper matte. It is interesting to note that the rarer oxyphile lead ores are associates of the already noted oxyphile *V,* and *Cr.*

Sn and *Ge* are concentrated in rocks rich in *Si* and *O* as one would expect. The association of *Ge* with *Zn* and of *Ga* with aluminum *oxide* is a by-product association and further emphasizes the fact that the definition of "ore" is complex and involves other factors than tonnage and tenor. On a tenor basis, *Ge* is a greisen associate of the oxyphile elements *Sn* and *W,* and *Ga* is a sulphophile associate of *Zn.*

The association of *Mo* and *Cu* is a sulphide association and the lack of associates for *Hg* may be explained by the uniquely volatile nature of the element.

It seems to the writer that it is remarkable that any semblance of physical-chemical periodicity appears in the associations of economic geology. Economic ore minerals and their elements can be translated from the primary magma chamber by any of a number of postulated mechanisms that may be classified roughly as magmatic, metallurgical, pneumatolytic, or hydrothermal. Further beneficiation may be metamorphic, supergene, or mechanical. In all of these processes the operative chemistry could be very complex as has been noted. We may never be able to assign the observed periodic association successfully to any specific geologic process, but from these observations the search appears nonetheless worthwhile.

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January 14, 1956

DISCUSSIONS

URANO-ORGANIC ORES OF THE SAN RAFAEL SWELL, UTAH

Sir: Discussion in ECONOMIC GEOLOGY (Vol. 50, No. 8, Dec.) by Davidson (10, p. 879) and Wright (28, p. 884) indicates that it may be advisable to call attention to recent observations on the urano-organic ores of the San Rafael Swell, Utah. The general occurrence of these ores in connection with the collapse features of Temple Mountain is already a matter of record (20). However, the nature and significance of the ores themselves is relevant to the discussion that has been taking place in this Journal.

Two general types of organic material: (1) fossil plant debris and (2) petroliferous substances are found in the ore-bearing strata of the San Rafael Swell. Studies show that fossil plant debris contains only trace amounts of uranium (15), and even uraniferous lignites seldom exceed 0.05 percent. Studies likewise indicate that petroleums in their original state contain no significant amounts of uranium (12).

The major coal fields of the Appalachian and mid-continent regions of the United States contain almost no uranium. In the Rocky Mountain region, however, certain large deposits of coal contain uranium (27). When found in subbituminous coals and lignites, uranium is apparently associated with the humic components of the coal probably as a urano-organic compound. The retention of uranium from solutions by the coal is not appreciably different for various low rank coals (5, 6). It would appear that coal, although ordinarily non-uraniferous, under favorable conditions may pick up uranium when in contact with uranium-bearing solutions.

Plant debris may be replaced by uraninite as illustrated by large logs that retain the appropriate wood structure although they have undergone complete replacement (21). It has been suggested that the uranium as complex uranyl carbonate or uranyl hydroxide ions in natural ore solutions was absorbed by the anthraxylon or attrital material and reacted with the organic sulfur or pyritic sulfur associated with the plant remains, being precipitated from solution as uraninite (var. pitchblende) (23). From this it has been assumed that the sulfide is genetically related to the carbonaceous material and controls the precipitation of the pitchblende. In the laboratory, uraninite has been precipitated between 25 degrees C and 260 degrees C. Crystallite study by Croft (8) suggests that coarser crystals result at the higher temperatures.

Numerous examples of plant debris unreplaced by uranium have been noted on the San Rafael Swell. In a large number of instances this is merely due to an absence of mineralization in a particular area. But even in areas where urano-organic ore is abundant, plant debris may be essentially uranium

free. In active areas the absence of plant debris replacement by uraninite may be attributed to two factors: (1) previous mineralization or coalification may have rendered the material unreceptive to the action of solutions, (2) nearby petroleum impregnated strata may have denuded the ore-bearing solutions of uranium ions by selective absorbtion leaving the debris unreplaced. The first alternative is illustrated by examples of silicified and pyritized logs and plant trash located in ore bodies, but free from uranium. The second is illustrated by lignitic but non-radioactive plant detritus at Temple Mountain surrounded by urano-organic ore due to the selective absorbtion of uranium from solution by the petroleum impregnated strata. Preliminary experiments on the relative abilities of coals and some other substances to remove uranium from solution under laboratory conditions show that low rank coals are more effective in the extraction of uranium since peats, lignites, and subbituminous coals may extract between 98 and 99.9 percent of the uranium from solution (24).

Urano-organic ore on the San Rafael Swell is found in areas believed to have been previously impregnated by petroleum. Organic material has become highly impregnated with uranium (up to 8 percent uranium excluding visible pitchblende particles). The resultant radioactive mass has in places replaced the quartz grains of the impregnated sandstone and in areas of highest uranium concentration relatively hard brittle urano-organic ore results. Although the properties of this material are not yet completely established, it appears to belong to the general group of materials to which the name thucholite has been applied as described by Ellsworth (11) from the vicinity of Parry Sound, Ontario; Barthauer, Rulfs and Pearce (3) from the Besner Mine, Ontario; Davidson and Bowie (9) for several foreign localities; Joubin (17) for the Blind River area, Canada; Bowie (4) for the Nicholson mine, Lake Athabasca, Canada; Robinson (26) for the Goldfields District, Saskatchewan; Kerr, Rasor and Hamilton (18) for Placerville, Colorado; and others. While these materials are all urano-organic compounds, it seems likely that they are subject to considerable variation.

It has been suggested by Breger (7) that the urano-organic material at Temple Mountain represents a lignitic extract and that the uranium and carbonaceous material entered the sandstone simultaneously in a nearly homogeneous suspension. Similarities were pointed out between certain coals and the urano-organic materials in insolubility, infra-red data and differential thermal analysis. However, recent differential thermal analyses of various ranks of coals and a few indurated hydrocarbons have been found to yield similar curves in several instances. It should also be noted that the solubilities of the indurated asphalts show a considerable range. It appears from preliminary data that the range of maximum temperatures of endothermic devolitilization and exothermic oxidation reactions between coals and indurated hydrocarbons (albertite, grahamite, wurtzilite) are similar, being characterized by only minor overlaps. The higher temperature exothermic reaction of "graphitization" (14) occurs at a slightly lower temperature in coals than in the hydrocarbons. In oxidation and devolitilization the urano-organic materials are similar to coals if one considers the variations between the two materials

significant; whereas the higher temperature reactions are more closely allied to the indurated hydrocarbons. Asphaltic pyrobitumens (elaterite, wurtzilite, albertite) are only slightly soluble in common organic reagents whereas asphaltites (gilsonite, grahamite) are generally soluble (1).

It would be difficult on the basis of field data to account for the mobilization, transportation and emplacement of relatively insoluble carbonaceous compounds. Further, field data indicate that large quantities of carbonaceous material adequate to form such compounds probably did not exist in the general area.

The emplacement of the uranium in the urano-organic material of the San Rafael Swell has been accompanied by the induration of the petroliferous material. The induration could have been accomplished by two general processes: (1) polymerization and (2) oxidation, or a combination of the two. Davidson and Bowie (9) and others have proposed radioactive polymerization for the urano-organic materials. However, a long time would be required for radioactive polymerization of large quantities of organic material in the Temple Mountain area, whereas field data suggest that the urano-organic compounds were formed in a relatively short geological time interval.

In a summary of the problem of sulphate reduction in deep subsurface waters, Ginter (13) has outlined two methods of reduction of sulphate in solution and attendant oxidation of hydrocarbon or carbonaceous material. The first method is the reduction of sulfate to sulfide by the hydrocarbons which in turn are oxidized to carbonate. It is pointed out that in the absence of oxygen this reaction would probably occur only at "high temperatures." The second method postulated is that anaerobic micro-organisms may cause sulfate reduction and oxidize hydrocarbons. Although sulphate-reducing anaerobes have been found in deep subsurface waters, the significance of the biochemical reactions has not been established.

Induration of petroleum may occur through long exposure to oxidizing conditions. Perhaps much of the non-uranium-bearing petroliferous material abundant on the San Rafael Swell has been indurated in this way. However, it is less indurated than the ore.

The influence of temperature on induration in at least some of the urano-organic substances is indicated by Ellsworth (11) who originally described thucholite as a primary hydrocarbon mineral. Davidson and Bowie (9) considered thucholite as belonging to a late hydrothermal stage. Bowie (4) considered thucholite formation associated with hydrothermal mineralization (4). Kerr, Rasor and Hamilton (18) consider the mineralization at Placerville, Colorado as hydrothermal. Abraham (1) and others consider the formation of asphaltic pyrobitumens and asphaltites as the gradual conversion of petroleum under the influence of time, heat and pressure.

It is generally known that oil when air blown in the vicinity of 200 degrees C will become indurated. Laboratory experiments by the writers have shown that the fluid tar at Temple Mountain can be partially indurated at temperatures between 150 and 200 degrees C when maintained for a number of days. A brittle, black, vitreous material similar in physical characteristics to the non-uranium asphalt at Temple Mountain is formed. Also the tar in contact

with uranium solutions under reflux conditions will pick up uranium from solution and when heated in the vicinity of 200 degrees C will also become partially indurated into a black, vitreous, brittle material. When this urano-organic material is leached with various acids and bases approximately 50 percent of the uranium is removed, and the organic compound is found to be only partially soluble in common organic solvents. The minimum temperature of induration has not been established, since the hardening is related in part to time.

The most likely hypothesis is that the induration of the hydrocarbon is caused by polymerization and oxidation of the oil by mineralizing solutions accompanied by more than normal heat.

Chemical analysis of the ore at Temple Mountain suggests that the uranium is present as a urano-organic compound perhaps as the uranyl ion (25).

Evidence of hydrothermal activity is suggested in the alteration of sediments accompanying the collapse features at Temple Mountain. Vertical halos of alteration border the collapse features in which iron, magnesium, calcium and carbonate have been removed from the Chinle formation and strata below and deposited at higher levels in Wingate sandstone as large masses of dolomite and siderite. At the same time the altered Chinle has suffered extensive development of kaolinite and illite.

The alteration and migration of carbonate was followed by sulphide mineralization with associated uranium deposition. The distribution of scattered occurrences has been found throughout a vertical range of some 1,200 feet from the middle of the Wingate sandstone to the top of the Coconino as established by diamond drill holes.

The sulphide mineralization has resulted in galena at the top of the Coconino sandstone, native arsenic and traces of sphalerite in a collapse area (19), and nodules of pyrite and urano-organic ore. Submicroscopic mineral particles occur in the urano-organic ore, which contains iron, arsenic, zinc, vanadium and chromium. A few X-ray diffraction patterns of the ore yield a portion of the diffraction pattern of arsenopyrite. Disseminated particles of uraninite are also scattered through the ore. Autoradiographs show that the distribution of the uranium is irregular and not always correlative to visible grains of pitchblende or secondary uranium minerals.

Although no witnesses were present in late Cretaceous or early Tertiary time to place a thermometer in the ore-bearing solutions, the weight of evidence as indicated above would favor hydrothermal conditions for the origin of the urano-organic ores of the San Rafael Swell. It is a simple matter to infer likewise that hydrothermal conditions have prevailed elsewhere in the formation of the primary uranium ores of the Colorado Plateau. Much evidence in support of this hypothesis exists, but this discussion is limited to observations on the San Rafael Swell.

The literature provides evidence that furnishes partial support to other theories concerning the initial source of the uranium in the Plateau area. These include the syngenetic theory as advanced by Wright (28) and others, or the ash-leach theory as set forth by Love (22), or the ground water theory (16), or the mechanical transportation theory (2).

A great volume of geological observation was released by workers on the Colorado Plateau at the Geneva Conference on the Peaceful Uses of Atomic Energy which summarizes years of effort by geologists of the Atomic Energy Commission, the U. S. Geological Survey and various universities (21). Important threads of evidence in favor of the hydrothermal theory for primary emplacement in many deposits may be found in these papers. It must be kept in mind that a number have not yet accepted this theory, notwithstanding the evidence that has been accumulated. While important progress has been made in recent years, a large amount of careful field observation and correlative laboratory study remain before a satisfactory explanation which will be universally convincing may be expected.

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ORIGIN OF THE RHODESIAN COPPER DEPOSITS

Sir: Mr. W. G. Garlick in the December issue of Economic Geology has attempted to answer some of the points I raised in a previous issue regarding the origin of the cupreous ores of Northern Rhodesia.

From reading Garlick's discussion the ores might be classed as supergene and epigenetic. He is evidently suggesting a transport by solution and for these ores to be syngenetic there would have to be a very careful timing between the erosion of the primary ore minerals and the deposition of the muddy facies in the stagnant water so that the solutions and muds arrived at the same time.

Garlick believes that the veining of the ore minerals and even the so-called pegmatite at N'Changa can be ascribed to metamorphism. To me, the grade of metamorphism is too low. I have always considered the Mine Series to be shales at about the Chlorite zone of Harker and Tilley. The growth of veins which is referred to by Eskola, Read and Turner would seem to demand that the rocks were at least schistose.

In my discussion I raised the question of Kipushi and the River Lode at N'Changa. To state that the mineralization at Kipushi is in the Kakontwe Limestone above the Kundulungu tillite is admitting that there have been hypogene epigenetic solutions operating in post-Mine Series times.

Mr. Garlick has not answered the query about the N'Changa River Lode.

Apparently the workers in this field all admit that the Mine Series has been intruded by gabbro. In place after place, from Labrador to the western edge of the Canadian Shield gabbro intrusions are followed by granite.

The Northern Rhodesian ores have associated cobalt. In the Congo, at Luushia they have uranium minerals associated with them. It is reported that at Shinkolobwe copper is associated with the radioactive minerals. At Kansanshi, cupreous veins cut the rocks and the ore minerals can be seen disseminated in the walls of the veins.

Lastly is it really possible to get chalcopyrite and bornite from covellite? F. W. Clarke in the Data of Geochemistry cites experiments by Durocher and others which suggest that covellite will be the mineral deposited in the

stagnant waters by the action of hydrogen sulphide. With temperatures of 100°–200° C chalcopyrite and bornite were prepared from the oxides.

I hope in the near future with some co-workers to complete a short paper dealing with some of these problems.

Even in Germany, the home of Schneiderhöhn, there is not unanimity concerning the disputed origin of the Kupferschiefer. "Truth is the daughter of time."

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REVIEWS

Beobachtungen an Türkischen Minerallagerstätten (Observations on Turkish Mineral Deposits). By ADOLF HELKE. Pp. 55–224; pls. 41; figs. 18. Neues Jahrbuch Mineralogie, Abhandlung 88, Heft 1, Stuttgart, 1955.

These notes on the mineral deposits of Turkey are a comprehensive assemblage of the author's extensive field observations in 1937–1938 and from 1950 to 1954 supplemented by a thorough survey of the literature and with mineral and rock determinations by colleagues in Europe.

Introductory to the discussion of the mineral deposits is a synopsis of the geography, geology, and structure, which includes a map of Turkey showing the drainage basins and a map showing the tectonic units. The latter map contains important Turkish place names, but there is no map showing the innumerable lesser localities mentioned in the accounts of the mineral deposits.

Though it is generally agreed that classification of ore deposits must be based on origin, Helke points out that origin can be variously interpreted, that by origin is sometimes meant the transition from mobile solution to crystallization or precipitation. This he says is but one episode in the development of an ore deposit, analagous to birth in the development of an organism. Thus related deposits (crystallizing under almost identical conditions), because of other geologic factors participating in their formation, can develop into a group of deposits of widely different appearances. The Turkish chrome deposits are regarded by Helke as typical examples of such heterogeneity in a genetic unit. He believes an ore deposit should be interpreted in the light of both content and tectonics, each of which may be endogene or exogene. Between these extremes are the volcanic exhalations which, although the content is endogene, show all of the petrographic characteristics of sediments, and hence are best considered exogene.

In the endogene deposits Helke places magmatic segregations, metamorphic deposits, contact metamorphic deposits, and hydrothermal deposits. The first three conform to definite tectonic concepts, whereas he considers hydrothermal an incongruous concept. Hydrothermal denotes merely hot aqueous solutions without reference to geotectonic position or source of the solutions. This inadequate concept, he says, has given rise to all kinds of circumloculations such as zonal theory, metallogenic provinces, etc. He includes only the first three groups in his descriptions of Turkish deposits. The only representatives of the magmatic segregations in Turkey are the chromite deposits. Metamorphic deposits are deposits of any origin that in the endogene realm were subjected to high temperature and pressure without reaching the magmatic condition. To this group are assigned certain chromite deposits in antigorite serpentine and numerous small iron and manganese deposits. In the contact metamorphic group the only significant Turkish examples are contact pneumatolytic deposits, though Helke says there is difficulty in deciding to what extent there was contact pneumatolytic transfer and to what extent metamorphic transfer of material. The most important example is the Divrik iron deposit, but molybdenite- and scheelite-bearing magnetite deposits and scheelite deposits are described.

Exogene deposits Helke says are practically equivalent to sedimentary. The processes of their formation are easier to follow than those of the endogene deposits. Since they are the products of the exogene cycle of events of weathering, erosion, transportation, deposition, and diagenesis, the exogene deposits can be classified in the natural order of these processes. In so far as the useful minerals are resistant, the exogene cycle is merely a mechanical cycle. In so far as new minerals are formed, they can be weathering products in place or the true sediments of a chemical cycle.

The exogene deposits of the mechanical cycle are subdivided primarily on the basis of their position, but in part on the basis of their nature, into eight groups—outcrop, talus, eluvial (creeping away from the outcrop), litter (scattered crusts of products of chemical weathering through mechanical transport), fanglomerate, "wildflysch" (exotic masses of economic significance in Cenomanian Flysch), river placers, and beach placers. Exogene outcrop deposits of chromite at Guleman and of hematite at Divrik have been worked. Chromite, emery, and hematite have been produced from eluvial placers. A hematite fanglomerate quarried at Divrik is estimated to contain one million tons of ore. Small amounts of emery and gold have been recovered from river placers.

The exogene deposits of the chemical cycle are classified as weathering deposits in place (residual), zones of weathering of hydrothermal deposits (not described because the hydrothermal deposits themselves are not included in the paper), and transported deposits or true sediments. Residual deposits of iron and manganese derived from protore, accumulations on limestone and on silicate rocks, and a false "iron hat" are described. At Deveci is a residual limonite deposit derived from sideritic limestone which is estimated to contain a half million tons of ore averaging 55 percent iron and 5 percent manganese. Though residual accumulations of iron ore on the ultrabasic rocks are widespread, none of economic importance are known. At Ergani Maden a lateritic blanket of limonite with 55 percent iron has accumulated far beyond the boundaries of a sulphide copper deposit, as a result of solution in depth during the wet season and capillary ascent and desiccation during the dry season. Occurrences of bauxite associated with limestone and of high-alumina clay in the footwall of coal seams are described.

As true sedimentary deposits of iron ore are cited large areas of Devonian ferruginous beds in northwestern Anatolia; an extensive deposit of montmorillonite in the Sakarya valley which is not of technical use because of its dolomite content; and salt pan accumulations in the steppes of inner Anatolia, of which the outstanding one is the Great Salt Sea with an area of 1,620 square kilometers from which there is an annual production of 120,000 tons of salt.

As volcanic exhalation deposits are described borate deposits, iron deposits, and manganese deposits. Most numerous and widespread are the manganese deposits that have been worked at many localities. Always associated with volcanic rocks, at some deposits the volcanic rocks predominate, at others limestone, or marl, or siliceous sediments. Both the manganese and the commonly associated silica are considered products of submarine volcanic exhalations. Most of the deposits are small and of the order of 200,000 tons appears to be the maximum.

Most extensively discussed are the chromite deposits, 52 pages being devoted to them. Helke says the variations in the chromite deposits are so bewildering that the only common relationship is that they are all magmatic differentiations in ultrabasic rocks. Generically the ultrabasic rocks are peridotites. They range in composition from dunite to harzburgite and lherzolite. The chrome ore bodies occur as intramagmatic schlieren and as magmatic segregations intruded into peri-

dotite, sometimes intergrown schlieren-like with the wall rock and sometimes in fault contact with it. In some cases the chromite bodies are intruded by peridotite. The peridotite may be fresh or serpentinized. Partly serpentinized rock is seldom encountered associated with the chrome ore bodies. Under tectonic stress the soft serpentine molded itself around the brittle chromite masses. Two types of serpentine occur. Under action of deep-seated magmatic waters, the olivine and pyroxene were pseudomorphosed to chrysotile without any change in the chromite bodies. Through dynamometamorphism antigorite developed. In the process, chrome ore bodies were broken and the pieces were dislocated and dragged as isolated "boudins."

The paper serves excellently as a reconnaissance survey of mineralization in Turkey through a wealth of cursory notes on countless occurrences. Without a good atlas or gazetteer of Turkey at hand, the reader is left with only a vague picture of their geographic distribution.

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Les Dislocations et la Croissance des Cristaux. By WILLY DEKEYSER and SÉVERIN AMELINCKX. Pp. 184; pls. 55; figs. 80. Masson et Companie, Paris, 1955. Price, 2,000 fr.

For one who is only partially familiar with current works in crystallography, it would be difficult to review this recent treatise from France without constantly keeping in mind its near counterpart in English, *Crystal Growth and Dislocations*, by A. R. Verma, which appeared in 1953. In this respect it is curious to find that Dekeyser and Amelinckx do not cite Verma's book, although they refer frequently to his works in scientific journals which appeared before and after 1953.

This newest book on the growth phenomena of crystals supplements Verma's book in some respects which I will mention presently, and should not be overlooked if for no other reason than its fine array of line drawings accompanying the text, and a section of 55 excellent photomicrographs at the end of the book. However, the chief value of the book which should place it in considerable demand is its up-to-date explanation of the complex stacking sequences in layer-structure minerals (polytypism).

The long standing mystery surrounding the phenomenon of polytypism is that a molecular layer seems to "know" when to repeat itself several tens or hundreds of Ångstrom units higher up in the crystal structure in the same sequence and orientation as the analogous layer far below it. Or so it would appear in a section parallel to the direction of repetition.

In Chapter 4, the authors treat polytypism as a rationally explained phenomenon attendant upon growth of layer-type crystals. In its early stages of formation, the "seed" crystal may relieve strain placed upon it during this initial period of growth by a dislocation, or offset, of the molecular layers. The dislocation will terminate inside the crystal. As a result of this, a step will emerge on the surface of the crystal, terminating as a wedge at the emergence of the dislocation axis. As growth units become attached to the crystal along this step, the crystal will grow by means of the helical winding of this step, or growth front, around the dislocation axis. If the height of the step produced by the dislocation is equal to the

unit cell height (the unit cell containing the layer-sequence that is to be repeated) then the growth of the mineral polytype is assured. One example that the authors give is the 6H type of silicon carbide. On the surfaces of such crystals, growth spirals are observed which have a height expected of them from previous unit cell measurements.

The ordered repetition of structure in polytypes has therefore been reconciled with the imperfect nature of nearly all common crystalline structures through the mechanism of helicoidal growth originating from screw dislocations.

As opposed to the calculated growth requirements of ideal crystals, the dislocation theory of growth offers a mechanism that allows growth from low degrees of supersaturation. The high degrees of supersaturation necessary for growth of ideal crystals is most unlikely in nature.

An interesting topic discussed by Dekeyser and Amelinckx that is not dealt with in Verma's book, is the utilization of polar diagrams to explain the complex interlacing of growth spirals. In effect, these are useful elaborations of Nabarro-Frank notations.

Another topic of similar interest, and only briefly treated at the end of the last chapter, is the growth of "whisker" crystals from tin and zinc plated surfaces. These thin crystal filaments have a yield strength which approaches the value of rupture of theoretically perfect crystal structures. As crystalline materials in general represent the most ordered arrangement of matter in the solid state, "whisker" crystals represent the most flawless crystalline material. In contrast with other crystals which represent aggregate growth from myriads of dislocations throughout the structure, a "whisker" filament may contain but one central dislocation as an extension of a dislocation beneath the base of the crystal. Practical application may some day be made of the exceptional yield strength of crystals of this type.

Dekeyser and Amelinckx devote the first two chapters to theoretical considerations of dislocations in crystal structures. The third chapter describes methods of observing growth spirals on crystal surfaces. The remaining chapters are concerned with polytypism, the formation of growth spirals, and interactions between different types of spirals. In the last chapter, the authors suggest that some of the dislocations which give rise to spiral growth may result when the dendritic portions of seed crystals meet as they enlarge.

Except for several inaccurate cross-references, the book is exceptionally clearly written and will be valuable to all who are interested in the mechanisms of crystal development.

GARY MCG. BOONE

YALE UNIVERSITY,
NEW HAVEN, CONN.

L'Exploitation des Richesses Minières du Congo Belge et du Ruanda-Urundi (Exploitation of the Mineral Wealth of the Belgian Congo and the Ruanda-Urundi). Pp. 163. Centre d'Information et de Documentation du Congo Belge et du Ruanda-Urundi, Bruxelles, 1955.

In publishing this report, the Information Center of the Belgian Congo has rendered a great service to the general public interested in this highly potential region. This compact and well-arranged brochure provides, through up-to-date statistics and a synthesis of the vast documentation accrued on the area, an over-all picture of the mineral industry of the Belgian Congo. Among the many features of this useful publication are a summary of the geology and formation of the min-

eralized areas; an alphabetical list of all mineral resources—exploited, exploitable and unexploited (though known); analyses of the deposits, composition, exploitation, metallurgy, production, markets (price, international agreements), enterprises, and uses of each of the major mineral products currently exploited—copper and associated metals, tin and associated products, gold, diamonds and coal; and, most convenient for the non-geologist, a lexicon of the geological terms used in the text.

This publication is indeed a welcome addition to the literature on the Belgian Congo as it not only provides the specialist with a most usable reference work, but, and this is probably its chief aim, will furnish a much larger public with a working knowledge of the impressive economic development of the region.

B. A. BROMBERT

NEW HAVEN, CONN.

Realms of Water. By P. H. KUENEN. Pp. 327; figs. 190; pls. 16. John Wiley & Sons, Inc., New York, 1956. Price, $6.50.

Dr. Kuenen's writings and researches emanating from his laboratory at the University of Groningen in Holland are well known on both sides of the Atlantic. His *Marine Geology* was welcomed a few years ago, and *Realms of Water* will be even more warmly welcomed.

This work deals with various features of physical geology, meteorology, oceanography, and glaciology as they apply to water and its movements. First, he traces the cycle of water and gives its properties. Succeeding chapters treat of water in the oceans, the atmosphere, in the solid state, in the ground, and on the surface. In the final chapter on "The Balance Sheet of Terrestrial Water" the author balances the various elements against each other. His discussion of oceanic waters reflects intimate knowledge gained from his participation in the Snellius Deep-Sea Expedition in the Moluccas. It includes oceanography in general, the ocean floor, tides and winds, circulation, turbidity currents, the effect of waves and currents, and evaporation. He tells of the conquest of the Zuider Zee and shows how oceanic circulation, temperature and salinity play a part in forming the climates and landscapes and their effect upon man.

Under atmospheric water, the author discusses heating and evaporation, condensation, cloud formation and precipitation. The discussion of water in the solid state is a treatment of glaciation dealing with snow to glacier ice, glacier movement, transportation, deposited detritus and the glacial epoch. Under ground water, the author disposes of many misconceptions and clarifies ground water movement, springs, geysers, drinking water, cave deposits, and karst topography. His longest chapter is on surface waters in which he considers erosional and transportation features, deposition of debris, turbulent flow and drainage patterns.

Dr. Kuenen is a gifted writer and brings vividness into his discussions. He has illustrated the book extensively, mostly by drawings. The book is an outstanding contribution to the broad and interesting subject of water.

ALAN M. BATEMAN

Der Bau der Südamerikanischen Kordillere. By HEINRICH GERTH. Pp. 264; figs. 62; tables 6; and 20 block-diagrams. Gebrueder Borntraeger, Berlin-Nikolasee, 1955. Price, DM 52,5.

This important book by Professor Gerth is the second volume (Band II) of his "Geologie von Südamerica" and deals with the South American Andes. The

First Volume (Band I) described the general geologic history of the South American continent, exclusive of the Andes and their orogenic history.

The volume represents a very laborious compilation of a great amount of geological material, almost all of it published by different South American Government agencies during the last 50 years or appearing in English and German publications abroad. However, the author states that some of the data he received through correspondence with many colleagues. As would be natural in a book of this order, much of the material is subject to further field studies, which have always been rather inadequate in the Andean regions.

Gerth divides his book into six principal Chapters, each dealing with a different part of the Andes. He digresses from the commonly accepted names of some of the Cordilleras and uses terms like "Antarktanden" for the Patagonian Cordilleras, "Peruanden" for the Cordilleras of Peru, and "Karibianden" for the Andean ranges of Ecuador, Colombia and Venezuela, irrespective of their geographical position, facing the Pacific or Atlantic Oceans. This, of course, differs from the generally accepted notions for the different Andean ranges (1).

In the Foreword of his book Gerth makes the statement that the geological knowledge of the Andean regions has been so advanced in recent years that the existing problems are mostly questions to be solved with larger scale mapping. With this opinion the reviewer will have to disagree. As a Geological Consultant to many South American governments the reviewer carried out extensive field studies over a period of many years (1930–1950) and happens to know that vast areas of the Andes are today geologically unexplored. The basic lack of geologic field data may not be apparent to the student of regional maps, but most field investigators of South American geology will concur with the reviewer that not only geological, but also basic topographical data, on which the geologic observations must be based, are in vast areas non-existent, or at best inaccurate (2).

The 20 (Blockdiagrammen) diagrams attached to the book are a very interesting and important part of the volume. They give a geological review of the Andes with numerous diagrammatic cross-sections. These clearly illustrate the typical block-faulted pattern of the structure of the Andes, where normal high-angle faults predominate, while low-angle faulting is rare and large-scale regional thrusting of an Alpine type is unknown. This has also been the long standing opinion and experience of the reviewer in the Andes. He quite agrees with Gerth's realistic interpretations as they are shown on his diagrams. The direct presentation of structural relations between rock units is, of course, essential for the correct understanding and interpretation of orogenic processes and their effect on the rise and evolution of mountain ranges.

It is interesting to note that Gerth dedicates several pages to an impartial analysis of the confusing interpretation of the structure of the Pirin area on Lake Titicaca in Peru (pp. 94–97). Heim (3) and Newell (4) studied that region in detail and arrived at diametrically opposite interpretations and cross-sections (p. 95, Fig. 26). Where Heim (3), with his knowledge of regional geology and his vast experience in Alpine tectonics, sees a normal, if faulted, succession of Tertiary and Cretaceous beds, such as is common in the adjoining Cuzco basin, Newell (4) appears confused in his stratigraphy and interprets the geology of the area, as affected by a vast overthrust produced by forces directed from the Western Cordillera against the Titicaca basin, as it also appears on his section. Gerth, after a lengthy discussion, comes to an obvious conclusion (p. 97), that there is nowhere in the Titicaca area an overthrust of the nature described by Newell. In Gerth's words, referring to faulting in the Pirin area (p. 97), ". . . und geben nirgends Veran lassung zu flachen Uberschiebungen." The reviewer had opportunity to visit the

region in question on several occasions (5) and he believes the region of the Titicaca basin in Peru and Bolivia is a natural continuation of the depressed Puno block. He also agrees with Gerth and Heim that there is no evidence for overthrusting in this part of the Andes, the structural pattern being clearly of normal faulting or block-faulting (1).

The reviewer is in accord with Gerth (p. 158) as to the structure of the Cordillera de Cutucu, in eastern Ecuador first studied and described by the reviewer (6) in 1938. Gerth (p. 133–134) also shares the reviewer's opinion (7) as to the hypothetical "borderland" off the Pacific coast of Colombia.

A short review is inadequate to treat the numerous interesting problems of Andean geology which are brought out and discussed by Gerth in considerable detail. It must, however, be said that new observations or contributions on the Andean geology are not apparent in this important volume. It is an excellently edited compilation and a very valuable contribution to South American geological literature for which Professor Gerth should be congratulated.

VICTOR OPPENHEIM

DALLAS, TEXAS,
April 8, 1956

REFERENCES

1. Oppenheim, Victor, 1947, Structural evolution of the South American Andes: Amer. Jour. Sci., vol. 245, p. 158–174.
2. Oppenheim, Victor, 1945, First generalized geologic map of South America: U. S. Section, Pan-American Inst. of Mining Eng. and Geology, no. 2, p. 1–12.
3. Heim, Arnold, 1947, Estudios Tectonicos del Campo Petrolifero de Pirin: Bol. Direc. Minas y Petrol., no. 79, Lima, Peru.
4. Newell, Norman D., 1949, Geology of the Lake Titicaca region, Peru and Bolivia: Geol. Soc. Amer., Memoir 36.
5. Oppenheim, Victor, 1944, Mapa Geologico Generalizado de Bolivia y Memoria Explicativa: Bot. Soc. Geol. del Peru, T. XVII, p. 3–22, Lima, Peru.
6. ——, 1950, The structure of Ecuador: Amer. Jour. Sci., vol. 248, p. 527–29.
7. ——, 1952, The structure of Colombia: Transact. Amer. Geoph. Union, vol. 33, p. 739–748.

Proceedings of the Conference on Latin-American Geology. Pp. 103; illus. University of Texas, Austin, 1955.

The conference on Latin-American Geology was held at the University of Texas under the joint sponsorship of the Department of Geology and the Institute of Latin-American Studies at the University. Its purpose was to bring together workers in the field of Latin-American geology in order to survey present knowledge and to direct attention to areas that require further investigation. This volume offers the papers presented at that meeting.

The book is made up of nine contributions. Four relate to petroleum geology—one on Mexico by E. J. Guzman, R. Suarez and E. Lopez-Ramos; another on problems of the Northern Maturin Basin, E. Venezuela by G. Rodriguez-Eraso; a third on geology and petroleum developments of Brazil (title only) by A. I. Levorsen; and a fourth on geologic development of the Colombian Andes by H. F. Belding. Two papers are on metallic resources, one on ore resources of Mexico by A. R. Geyne, and another on mineral resources of Brazil by W. D. Johnston, Jr. Another paper is by G. H. Hazen on Gravity of Columbia: Gravity as a Reconnaissance Geological Tool. Two abstracts are included, one on Contributions and Aids by Geographers to Latin-American Geology and Geologists, by D. B. Brand, and Research on Central American Volcanoes, by F. M. Bullard.

This is a good start to a better understanding of Latin-American geology and it is hoped that this volume will be just the first of others to follow.

BOOKS RECEIVED

KURT SERVOS

Travaux des Collaborateurs. Pp. 668; illus. Service de la Carte Géologique de l'Algérie, Bull. 5, Alger, 1955. *Twenty papers deal with stratigraphy, sedimentary petrology, paleontology, and structural geology.*

Etude Géologique Préliminaire des Conglomerats Diamantifères d'Age Mésozoique au Kasai. C. FIEREMANS Pp. 225–294; pls. 8. Institut Géologique de l'Université de Louvain, Mém. Tom. XIX, Louvain, 1955. *This is a preliminary geologic study of a very extensive Mesozoic diamond-bearing conglomerate in the Belgian Congo.*

The Geology and Mineral Resources of the Kuching-Lundu Area, West Sarawak, including the Bay Mining District. G. E. WILFORD. Pp. 254; pls. 51; figs. 32; tbls. 31. Geological Survey Dept. British Territories in Borneo, Kuching, Sarawak, 1955. Price, M$6.00. *Gold is the principal economic mineral and a large bauxite deposit was only recently discovered. Geologic maps, 1:50,000 and 1:125,000.*

Argilas e Minerais Afins. Y. S. VISCONTI. Pp. 189; figs. 43. Instituto Nacional de Tecnologia, Rio de Janeiro, 1951. *This monograph on the clay minerals is essentially a collation of the literature.*

Fifth Annual Report. Pp. 151. National Advisory Comm. on Research in the Geological Sciences, Geological Survey of Canada, Ottawa, 1955. Price, 50 cts.

Earthquakes in Kern County, California During 1952. G. B. OAKESHOTT, Editor. Pp. 283; pls. 2; California Division of Mines, Bull. 171, San Francisco, 1955. Price, $4.00. *The Arvin-Tehachapi earthquake, the most completely investigated earthquake in this country's history, was second in destructiveness only to the shock of 1906. This volume contains discussions of the geologic features, surface ground effects, and structural damage induced by the earthquake. Some 36 authors cooperated in authorship of this very valuable bulletin, segmented into three categories: Geology, Seismology, and Structural Damage.*

Instrumentation and Methods for Radioactivity Detection in the Mineral Industry. J. O. MILMOE and S. P. KANIZAY. Pp. 97; pls. 3; figs. 28; tbls. 4. Quarterly Colorado School of Mines, Vol. 51, No. 1, Golden, 1956. Price, $1.00. *This comprehensive guide on the nature of radioactivity and the instruments and techniques used in its detection and measurement should be useful to geologists.*

Report of the Director of Geological Survey, 1953–54. Pp. 15; figs. 8. Geological Survey, Accra, Gold Coast, 1955. Price *Shs. 2/6. None of the many economic mineral deposits seems to have commercial possibilities.*

Statistical Summary of the Mineral Industry. Pp. 359. Colonial Geological Surveys, London, 1956. Price, *£1.7s.6d.*

Groundwater in Northwestern Illinois. J. E. HACKETT and R. E. BERGSTROM. Pp. 24; figs. 8. Illinois Geological Survey, Circ. 207, Urbana, 1956.

Underground Storage of Liquid Hydrocarbons in Indiana. J. B. PATTON. Pp. 19; pl. 1; fig. 1; tbl. 1. Indiana Geological Survey, Rept. of Progress No. 9, Bloomington, 1956. Price, 50 cts. *All the Paleozoic bedrock systems contain potential reservoir sites.*

Progress Report on the Groundwater Hydrology of the Equus Beds Area, Kansas. G. J. STRAMEL. Pp. 59; pl. 1; figs. 31; tbls. 5. Geological Survey of Kansas, Bull. 119, Pt. 1, Lawrence, 1956.

Groundwater Resources of Southeastern Oakland County, Michigan. J. F. FERRIS, E. M. BURT, G. J. STRAMEL and E. G. CROSTHWAITE. Pp. 158; pls. 6; figs. 44; tbls. 9. Michigan Geological Survey, Progress Rept. No. 16, Lansing, 1954.

Geomagnetic Survey of the Tioga Area, North Dakota. MILLER HANSEN. Folded sheet. North Dakota Geological Survey, Rept. of Inv. 21, Grand Forks, 1956. *The area includes two major and five minor oil fields.*

Annual Report of the Year ended 31st December, 1954. Pp. 27. Geological Survey Dept. of Nyasaland, Zomba, 1955. Price, *Shs.* 2/6.

Geologist. Pp. 98. Osmania University, Hyderabad, 1955. *This is the first issue of a new journal to be published yearly under the auspices of the Geology Association of Osmania University.*

Les Mastodontes Miocénes du Portugal. F. M. BERGOUNIOUX, GEORGES ZBYSZEWSKI, and F. CROUZEL. Pp. 139; pls. 60. Services Géologiques du Portugal, Mém. No. 1, Lisbon, 1953.

Report of the Geological Survey for the Year 1954. Pp. 24. Geol. Survey of Sierra Leone, Freetown, 1956. Price, *Shs.* 2/–.

Minerals Yearbook, Volume II, Fuels. Pp. 478. Bureau of Mines, Fuels and Explosives Division, Washington, D. C., 1956. Price, $2.25. *Total new energy supply in 1953 was 39.2 quadrillion B.t.u. Industry drilled more than 48,000 wells, of which 25,762 were commercial oil producers, 3,086 gas wells, and the rest dry holes.*

University of California—Berkeley and Los Angeles, 1955.

Pub. in Geological Sciences, Vol. 31, No. 4. Classification of Clypeasteroid Echinoids. J. W. DURHAM. Pp. 78–198; pls. 2; figs. 38. Price, $2.00.

Pub. in Geological Sciences, Vol. 32, No. 1. Volcanism in the Southern Part of El Salvador. HOWELL WILLIAMS and HELMUT MEYER-ABICH. Pp. 64; pls. 8; figs. 7. Price, $1.00.

Geological Survey of Great Britain—London, 1955.

Bull. No. 9. Pp. 58; pls. 3; figs. 8. Price, 6*s.*

Bull. No. 10. Pp. 80; pls. 4; figs. 28. Price, 8*s.* 6*d.* *Five papers deal with radioactivity. The minimum age of initial mineralization of the Witwatersrand is 2,000 million years, but there is evidence that the reefs have been reworked to provide several generations of uraninite. Another paper, on the impersistence of uraninite as a detrital mineral, shows that the placer origin of pitchblende-uraninite deposits in the sedimentary rocks of Witwatersrand and of Colorado Plateau is untenable.*

Geological Survey of Japan—Hisamoto-Cho, Kawasaki-shi, 1955.

Mikawa-ono (Kyoto, No. 47). MASATSUGU SAITO. Pp. 47. *Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Suzaka (Niigata-97). RYOHEI OTA and MASATO KATADA. Pp. 60. *Ore deposits includes sulphur (impregnation replacement), bog iron ore, and refractory materials. Text in Japanese, résumé in English. Geologic map, 1:50,000.*

Ohio Geological Survey—Columbus, 1956.

Inf. Circ. No. 18. An Application of Business Machine Technique to Stratigraphic and Coal Resources Studies. W. H. SMITH, R. A. BRANT, and M. S. KLEIN. Pp. 26; figs. 10. Price, 25 cts.

Rept. of Inv. No. 27. Petrographic Constitution of the Meigs Creek No. 9 Coal Bed. G. H. CADY and G. E. SMITH. Pp. 97; pl. 1; figs. 30; tbls. 10. Price, 97 cts. *This comprehensive study of the banded structure in a coal bed is based on polished surface technique.*

Ontario Department of Mines—Toronto, 1956.

Geol. Circ. No. 4. Preliminary Report on the Geology of the Jackfish-Middletown Area. J. W. R. WALKER. Pp. 6. *Gold, copper, lead, zinc, silver, molybdenum, and iron comprise the mineralization. Geologic map, 1:63,360.*

Geol. Circ. No. 5. Preliminary Report on the Geology of the Populus Lake Area. J. C. DAVIES and S. N. WATOWICH. Pp. 3. *Minor sulphide mineralization is common throughout the metamorphic terranes. Geologic map, 1:63,360.*

Sixty-fourth Annual Rept., Vol. LXIV, Pt. 4. Geology of the O'Sullivan Lake Area. W. W. MOORHOUSE. Pp. 32; figs. 8. *The area has possibilities as a gold producer and has indications of copper and silver mineralization. Geologic map, 1:12,000.*

Tanganyika Geological Survey—Dar-es-Salaam, 1955.

Bull. 26. The Geology and Ecology of the Nachingwea Region. D. R. GRANTHAM and R. D. PILSON. Pp. 33; pls. 3. Price, *Shs.* 7/50. *Limestone, graphite, and gold are the principal mineral potentials. Geologic map, 1:125,000.*

Bull. 27. The Geology of the Songwe-Kiwira Coalfield, Rungwe District. D. A. HARKIN. Pp. 33; pls. 9; Price, *Shs.* 7/50. *The coal measures conformably overlie basal conglomerates and sandstones of the Karroo System. Geologic map, 1:50,000.*

U. S. Geological Survey—Washington, D. C., 1955.

Prof. Paper. 274-F. Middle Ordovician Rocks of the Tellico-Sevier Belt, Eastern Tennessee. R. B. NEUMAN. Pp. 141–178; pls. 4; figs. 3; tbls. 3. Price, 75 cts.

Bull. 975-D. Geology of South-central Oriente, Cuba. G. E. LEWIS and J. A. STRACZEK. Pp. 171–336; pls. 4; figs. 225; tbls. 3. *Approximately 783,000 long tons of manganese concentrates and crude ore were produced from the area 1942–45.*

Bull. 1009-M. Botanical Prospecting for Uranium on La Vantana Mesa, Sandoval County, New Mexico. H. L. CANNON and W. H. STARRETT. Pp. 391–407; figs. 6; tbls. 3. Price, 15 cts.

Bull. 1021-F. Ordovician and Silurian Coral Faunas of Western United States. HELEN DUNCAN. Pp. 209–236; pls. 7; fig. 1. Price, 15 cts.

Bull. 1027-D. Geology and Mineral Fuels of Parts of Routt and Moffat Counties, Colorado. N. W. BASS, J. B. EBY and M. R. CAMPBELL. Pp. 143–250; pls. 10; figs. 2; tbls. 11. *Coal of all ranks, oil, and gas comprise the major mineral resources of the area.*

Bull. 1027-E. Sugar Loaf and St. Kevin Mining Districts, Lake County, Colorado. Q. D. SINGEWALD. Pp. 251–299; pls. 2; figs. 8. Price, 75 cts. *Veins containing silver, gold, zinc, and some lead, occupy fissure zones in greatly shattered and intensely altered wallrock.*

Bull. 1036-E. An Application of Spectrographic Microphotometric Scanning. C. L. WARING, MONA FRANCK, and A. M. SHERWOOD. Pp. 69–80; tbls. 4. Price, 15 cts.

Bull. 1041-A, B. Coalfields of the Republic of Korea, Pt. I. D. A. ANDREWS and CHEONG CHANG HI. Pp. 1–10; fig. 1. Price, 15 cts. *Coal is widely distributed in Korea in rocks of Permian, Jurassic and early to middle Cenozoic age.*

Water-Supply Paper 1263. Geology and Ground-Water Resources of the Missouri River Valley in Northeastern Montana. F. A. SWENSON. Pp. 128; pl. 1; figs. 18; tbls. 9. Price, $1.25.

Water-Supply Paper 1255. Water Resources of Southeastern Florida. G. G. PARKER, G. E. FERGUSON, S. K. LOVE, and others. Pp. 965; pls. 24; figs. 223; tbls. 147.

ERRATUM

In the March-April issue of this JOURNAL, the Quarterly of the Colorado School of Mines, Vol. 50, No. 3, was incorrectly described in the section *Books Received.* The description is to read as follows: This publication summarizes the field of engineering geology and is useful as a text in that subject. Engineering geologists will also find the references helpful.

SCIENTIFIC NOTES AND NEWS

SCIENTIFIC NOTES AND NEWS

THE U. S. ATOMIC ENERGY COMMISSION has concluded arrangements with the OHIO OIL COMPANY, in association with Arthur E. Pew, Jr., of Philadelphia, under which the Commission has given assurance of its willingness to negotiate a contract for purchase of a specified quantity of uranium concentrates to be produced from uraniferous lignites from the western Dakotas. The Ohio Oil Company and Mr. Pew are currently conducting development work on a process which they believe will be economic for processing the lignites, and the Catalytic Construction Company has been retained to proceed with pilot plant operations.

PAUL WEAVER, Distinguished Research Geologist at Texas A. & M. College, and CLARENCE L. MOODY, consulting geologist in Houston, have been elected to Honorary Membership in the American Association of Petroleum Geologists for distinguished service in the field of petroleum geology.

JAMES LAW, geologist, The California Standard Company, Calgary, Alberta, and LIEUTENANT ROBERT H. DOTT, JR., Air Force Cambridge Research Center, Bedford, Mass., were chosen to receive the President's Award of the A.A.P.G. at the Association's annual convention in Chicago, April 24.

THE UNITED STATES CIVIL SERVICE COMMISSION has announced an examination for filling Geophysicist positions in the Coast and Geodetic Survey, other Federal agencies in Washington, D. C., throughout the United States, and some overseas. The salaries range from $4,345 to $11,610 a year. Appropriate education and experience are required. For positions paying from $4,345 to $5,440 a year, education alone may be qualifying. No written test is required. Application forms may be obtained at many post offices, or from the U. S. Civil Service Commission, Washington 25, D. C. Applications will be accepted by the Board of U. S. Civil Service Examiners, Coast and Geodetic Survey, Department of Commerce, Washington 25, D. C., until further notice.

JOHN R. RAND, Portland, Me., has been elected to the Board of Directors of Copper Range Company. Rand, a graduate of Harvard, is at present geologist to the chairman of Industrial Development Commission of the State of Maine.

MICHIGAN TECH was host to an Institute on Lake Superior Geology held at Houghton, May 11 and 12. Co-sponsors were the Geological Survey of Michigan and the Exploration Subsection of the Upper Peninsula Section of American Institute of Mining, Metallurgical and Petroleum Engineers. Through the cooperation of the U. S. Geological Survey, the Geological Survey of Canada, the Ontario Department of Mines, the U. S. Atomic Energy Commission, the Aero Service Corporation and the mining industry, the Institute's program theme was Geological Exploration. The program highlights included the Michigan Copper District, Uranium and Base Metal Exploration in Ontario, Geophysical Studies in the Lake Superior District including Canada, Beneficiation Characteristics of Michigan Iron Ores, Geochemical Exploration and Photogeology, with papers by recognized

experts. A representative of the U. S. Atomic Energy Commission spoke on Nuclear Energy and Its Impart on the Mineral Industries. There were exhibits and demonstrations of photogeological and photogrammetric work.

HUGH C. MORRIS is a geologist at the Sullivan mine, Canadian Mining & Smelting Co., Kimberly, B. C.

LEWIS E. SCOTT, geologist, construction department, Oregon State Highway Commission, Salem, Ore., is with the U. S. Bureau of Public Roads, San Jose, Costa Rica.

W. J. RUNDLE, formerly associate professor of mining and metallurgy, University of Wisconsin, Madison, is with Cyprus Mines Corp., Los Angeles.

GEOCHIMICA ET COSMOCHIMICA ACTA announces a special double issue for July–August, 1956, that will contain the following papers: *Silica in Hot-Springs Waters,* by Donald E. White, W. W. Brannock and K. J. Murata, U. S. G. S.; *Dissolution and Precipitation of Silica at Low Temperatures,* by Konrad B. Krauskopf; *Potassium-Argon Dating,* by R. E. Folinsbee. Subscribers may obtain extra copies for $4.20; non-subscribers for $7.00. Orders may be sent to the Pergamon Press, Inc., 122 East 55th Street, New York 22, New York.

The Department of Cultural Affairs of the Pan American Union and the School of Inter-American Studies of the University of Florida at Gainesville are sponsoring a survey of investigations in progress in the field of Latin American studies. Questionnaires have been sent to faculty members and graduate students in all disciplines, and to independent scholars and researchers who may have investigations under way connected with Latin America. Those who do not receive questionnaires are urged to request them from the School of Inter-American Studies, University of Florida, Gainesville, Fla., in order that the published results may be as complete as possible. Distribution of the completed survey is scheduled for early fall.

JOHN D. HESS has opened a practice as consulting ground-water geologist with offices located in El Centro, California. He is also director of Valley Analytical and Testing Laboratories, Inc., and will offer services in the fields of geochemical interpretation of waters and drainage.

GEORGE A. KIERSCH resigned as associate professor, University of Arizona geology department last summer and since has devoted most of his time to completing the Mineral Resources Survey of the Navajo country, Arizona-Utah. Dr. Kiersch has been serving as director of this project which is investigating the mineral resources of 11 million acres of Indian lands. The project will be completed during the course of 1956 when results will become available through the Bureau of Indian Affairs, Window Rock, Arizona.

JOHN G. BROUGHTON, State Geologist of New York, announces that a new list of sales publications has been compiled by the New York State Museum and is available without charge on request to the Museum at Albany 1, New York. The revised list includes a considerable number of geological and paleontological bulletins, circulars, etc., that were formerly considered out of print and have been available only through dealers. The stock of some of these items is small; in such cases, preference will be given to orders from libraries of universities, foundations and other organizations.

BLAIR W. STEWART has been appointed to the California State Mining Board. A vice-president of the Coronado Copper & Zinc Co., Mr. Stewart has been active in the Southern California section, AIME.

FELIX E. WORMSER, Assistant Secretary of the Interior, is the 1956 recipient of the Egleston Medal. This is Columbia University's highest award for distinguished engineering achievement. Mr. Wormser, currently one of the six alumni trustees of Columbia University, is a graduate of the School of Engineering, 1916. He was vice-president of the St. Joseph Lead Co., and president of the Lead Industries Assn., prior to his appointment to the Department of the Interior.

LOUIS S. CATES, chairman of the board, Phelps Dodge Corp., New York, has been awarded the gold medal of the Mining and Metallurgical Society of America.

G. B. GRISWOLD has joined the Wah Chang Mining Corp., Bishop, Calif., as a mining engineer.

CLARENCE E. NELSON is resident engineer, mining department, American Smelting & Refining Co., New York. Mr. Nelson was transferred from Buchans, Newfoundland.

CHARLES WILL WRIGHT, vice-president, World Mining Consultants Inc., New York, has recovered from the automobile accident he was in last May. Shortly before his accident Mr. Wright was in Sicily examining the sulfur mines. He is returning there for Sicilian American Sulphur Co.

FRANCIS R. JOUBIN, managing director of Technical Mine Consultants Ltd., Toronto, president of Algom Uranium Mines Ltd., and vice-president of Pronto Uranium Mines Ltd., was the Canadian guest speaker at the Nuclear Science Congress and International Atomic Exposition held in Cleveland last December.

W. P. JOHNSTON, former field geologist for the New Jersey Zinc Co., has set up a mining geology consulting practice. His address is: 3200 West Plumb Lane, Reno, Nevada.

CORNELIUS BLOOT, formerly geologist, Bureau of Mines & Geology, Monrovia, Liberia, is mining engineer, Corporación Minera de Bolivia, Catavi, Bolivia.

H. A. R. SMITS, formerly exploit engineer, Comité National du Kivu, Costermansville, Belgian Congo, is now with Kamativi Tin Mines Ltd., Dett, Southern Rhodesia.

RODERICK G. MURCHISON, formerly vice-president and general manager, Minerals Research & Development Corp. in British Somaliland, is now resident geologist with Tin & Associated Minerals Ltd., Jos, Northern Nigeria.

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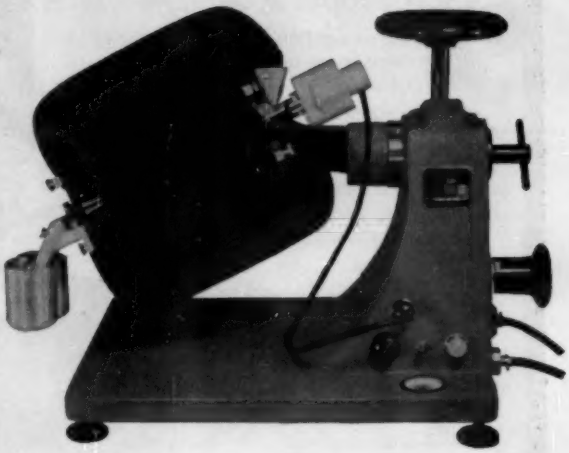

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